Lightning Induced Over-voltages in Nuclear Power Plants

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ABSTRACT OF THE
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Lightning is an important meteorological process that has vital possible effects on power systems. When a transmission tower is subjected to a lightning stroke, all the equipment in the power system is jeopardized by the induced over-voltages. This study analyzes the lightning induced over-voltages in two different nuclear power plants and proposes protection methods to keep the over-voltages under basic insulation levels of the equipment.

Two standard lightning currents of 200 kA 1.2/50 μs and 20 kA 1.2/50 μs have been studied. A lightning source, transmission towers, overhead lines and a surge capacitance have been modeled for both nuclear power plants. For the first nuclear power plant, power transformers of 415/21.5 kV, 15.75/6 kV, and 6/0.4 kV and surge arresters for 400 kV, 15.75 kV, and 6 kV levels have been modeled. For the second nuclear power plant, power transformers of 415/21.5 kV, 20/6.9 kV, 6.9/0.69 kV, and 690/400 V and surge arresters for 400 kV, 20 kV, and 6.9 kV levels have been modeled properly. ATPDraw software, which is a version of EMTP, has been used for the simulations of the overall models. Several scenarios with different numbers of transmission towers, different cases with the combinations of surge arresters, and the effect of the surge capacitance have been investigated. Applicable protection methods with the surge arresters have been proposed according to basic insulation levels.

Keywords: ATPDraw, Basic Insulation Level, Lightning, Nuclear Power Plant, Over-voltage, Power Transformer, Surge Arrester, Surge Capacitance

Preface

This thesis work has been carried out in the Research Group of Power Systems and High Voltage Engineering at Aalto University School of Electrical Engineering, Department of Electrical Engineering and Automation between May 2018 and November 2018.

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I am grateful for my parents for everything. I would like to thank Finland and my beautiful hometown, Turkey.

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Otaniemi, 26.11.2018

Ismet Tuna Gürbüz

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Symbols and Abbreviations

Symbols

α	Attenuation Coefficient
b	Susceptance per Length
C	Capacitance
C_0	Propagation Velocity
C_{A}	High Voltage Side Capacitance of Phase A of the Transformer
C_{Aa}	Capacitance Between High and Low Voltage Sides of Phase A of the Transformer
C_{ab}	Low Voltage Side Capacitance Between Phases A and B of the Transformer
C_{B}	High Voltage Side Capacitance of Phase B of the Transformer
C_{Bb}	Capacitance Between High and Low Voltage Sides of Phase B of the Transformer
C_{bc}	Low Voltage Side Capacitance Between Phases B and C of the Transformer
C_{C}	High Voltage Side Capacitance of Phase C of the Transformer
C_{Cc}	Capacitance Between High and Low Voltage Sides of Phase C of the Transformer
C_{ca}	Low Voltage Side Capacitance Between Phases C and A of the Transformer
C_{H}	High Voltage Side Capacitance of One Phase of the Transformer
C_{HL}	Capacitance Between High and Low Voltage Sides of One Phase the Transformer
C_{L}	Low Voltage Side Capacitance of One Phase of the Transformer
C_{S}	Stray Capacitance of One Phase of the Transformer
C_{Sa}	Stray Capacitance of Phase A of the Transformer
C_{Sb}	Stray Capacitance of Phase B of the Transformer
C_{Sc}	Stray Capacitance of Phase C of the Transformer
g	Conductance per Length
L	Inductance
L_{A}	High Voltage Side Inductance of Phase A of the Transformer
L_{ab}	Low Voltage Side Inductance Between Phases A and B of the Transformer
L_{B}	High Voltage Side Inductance of Phase B of the Transformer
L_{bc}	Low Voltage Side Inductance Between Phases B and C of the Transformer
L_{C}	High Voltage Side Inductance of Phase C of the Transformer
L_{ca}	Low Voltage Side Inductance Between Phases C and A of the Transformer
L_{H}	High Voltage Side Inductance of One Phase the Transformer
L_{L}	Low Voltage Side Inductance of One Phase the Transformer
r	Resistance per Length
R	Resistance
T_1	Front Time
T_2	Time to Half Value of a Decreasing Voltage, Tail Time
T_p	Time to Peak Value
T_t	Total Over-voltage Duration
V_{in}	Input Voltage
V_{out}	Output Voltage
x	Reactance per Length
X	Reactance
Z	Impedance
Z_0	Surge Impedance
Z_{f}	Footing Resistance
Z_{Tr}	Coil Impedance of the Transformer

Abbreviations

ATP	Alternative Transients Program
BIL	Basic Insulation Level
COV	Continuous Over-voltage
EMTP	Electro Magnetic Transients Program
FRA	Frequency Response Analysis
HV	High Voltage
LV	Low Voltage
NPP	Nuclear Power Plant
RV	Residual Voltage
TOV	Temporary Over-voltage

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1 Introduction

Lightning is an electrostatic discharge that occurs when the breakdown strength of air is exceeded during a thunderstorm. It is an extremely important meteorological process that has negative impacts on both world and human being by causing financial and moral damages. From power systems point of view, there are potential irreversible damages that lightning may cause. When the lightning strikes to a power system, the equipment of the system is exposed to transient over-voltages induced by the lightning. These transient over-voltages generates traveling waves having large voltage magnitudes. If the protection is not sufficient enough, the magnitude of the induced over-voltages may exceed the BIL of the equipment resulting in a catastrophe in the system which makes the system unreliable and insecure.

Usually, there are 2 different ways of damage given by the lightning. The first one is that voltage across the equipment increases above a limit causing a discharge between the terminals, which gives a permanent damage to the electrical insulation of the equipment. The second one is that the equipment may melt or be broken if the energy handling capacity of the equipment is less than the energy of the lightning [1]. From insulation coordination point of view, it is necessary to investigate the effect of lightning on the power system to protect the parts of the networks as transmission and distribution towers, overhead lines, underground cables, transformers, substations, and loads properly. To achieve this, a true understanding of transient over-voltage theory and a suitable modeling of the system is needed.

The aim of this thesis is to analyze the lightning induced over-voltages in nuclear power plants (NPP) by proposing applicable models. Two different NPPs have been studied in this work. Systems exposed to the lightning stroke composed of transmission towers, overhead lines, power transformers, and surge arresters have been modeled and simulated using a simulation software called ATPDraw which is a version of EMTP. Firstly, the lightning source has been modeled as a current source. Then, transmission towers have been modeled by finding the equivalent circuit in terms of R, L, and C components. Overhead lines that connect transmission lines have been modeled by PI equivalent model approach. 415/15.75 kV transformer of the first NPP and 415/21.5 kV transformer of the second NPP have been modeled by using FRA of the transformers. 15.75/6 kV and 6/0.4 kV transformers of the first NPP and 20/6.9 kV, 6.9/0.69 kV, and 690/400 V transformers of the second NPP have been modeled as in the similar study of Nehmdoh A.Sabiha [2]. Next, the surge arresters in each voltage level of both NPPs have been modeled by using Pinceti Model approach. After the implementation of the model of each part into ATPDraw software, 4 main studies of lightning stroke for both NPPs have been carried out with different magnitudes and locations as

- 200 kA 1.2/50 μs direct stroke to the ground wire
- 20 kA 1.2/50 μs direct stroke to the Phase A conductor
- 20 kA 1.2/50 μs direct stroke to the Phase B conductor
- 20 kA 1.2/50 μs direct stroke to the Phase C conductor.

During the simulations, there are 4 available transmission towers. Different scenarios have been conducted with different numbers of existing towers and different locations of the stroke. Moreover, different cases with various combinations of surge arrester operations have been investigated. By using several cases and scenarios, induced over-voltage magnitude on each phase of each voltage level has been measured and recorded. They have been compared with the BIL of each voltage level, and a safe case for each scenario has been tried to be found. The background of the over-voltages, lightning phenomenon, modeling of the system, simulations and results, and the discussions on the results will be given in the next parts of the thesis in detail.

1.1 Thesis Objectives

The main objectives of this thesis study can be represented as follows:

- To model a power system consisting of transmission towers, overhead lines, power transformers, and surge arresters for applicable simulations.
- To simulate the different magnitudes of the lightning stroke to the ground and phase conductors of a transmission tower in ATPDraw software.
- To analyze the transient over-voltages induced by lightning strokes for different cases of surge arrester operation, and different scenarios of network structure.
- To investigate the effect of a surge capacitance usage in the network in terms of induced over-voltage magnitudes.
- To propose a protection way for the equipment of the network from the insulation coordination point of view.

1.2 Thesis Structure

The thesis has been divided into 5 main chapters as: Introduction, Background, Modeling of the System, Simulations and Results, and Conclusion.

Chapter 1: In this chapter, the general introduction of the thesis is made. The lightning phenomenon and its effects on a power system are summarized briefly. The main steps of the thesis work are explained concisely. The main objectives of the thesis and thesis structure are given.

Chapter 2: In this chapter, background information of the main study is given with the topics of Low-Frequency Over-voltages, Transient Over-voltages, Lightning, and Over-voltage Protection for a better comprehension.

Chapter 3: In this chapter, proposed models of each part of the systems are explained with the broad justifications and theoretical calculations. The single line diagrams of the NPPs that this thesis focuses are demonstrated in the beginning. Afterward, the modeling of the lightning source, transmission towers, overhead lines, power transformers, and surge arresters are shown separately. At the end of the chapter, the overall simulation model are presented.

Chapter 4: In this chapter, the simulation procedure and simulation results are presented in detail. Different scenarios and cases used in the simulations are explained and investigated. The discussions and comments on the simulation results are made rigorously.

Chapter 5: In this chapter, the discussions made on the results of the simulations are evaluated, and the thesis study is concluded.

2 Background

In power systems, the equipment and network parts are designed to operate within the voltage limits. If the design limit of the voltage is exceeded due to different causes, over-voltage occurs in the system. Over-voltages can be divided into 2 main groups in terms of the generation ways as externally generated over-voltages and internally generated over-voltages. The first group over-voltages are caused by the external causes or environmental effects. The second group over-voltages are generated due to operation conditions of the network [3]. Those different causes of over-voltages lead to different electric stress on the system. In terms of dielectric stress classes, over-voltages are divided into 2 main categories as

– Low-frequency over-voltages

– Transient over-voltages.

2.1 Low-frequency Over-voltages

Low-frequency over-voltages are of long duration within the specified intervals. The over-voltages that occur during the low-frequency intervals usually have regular shapes. They can be divided into 2 subcategories in terms of the duration and magnitude of the over-voltage as

– Continuous (power-frequency) over-voltages

– Temporary (sustained) over-voltages.

In this part, these over-voltage types and their standard characteristics will be explained and shapes of them will be shown. Before explaining these over-voltage types, some of the abbreviations used in the figures will be explained as

$\boldsymbol{T_1}$, $\boldsymbol{T_f}$ **:** Front time

$\boldsymbol{T_2}$ **:** Time to half value of decreasing voltage, tail time

$\boldsymbol{T_t}$ **:** Total over-voltage duration

$\boldsymbol{T_p}$ **:** Time to peak value

$\boldsymbol{f_1}$ **:** Frequency of front time

$\boldsymbol{f_2}$ **:** Frequency of tail time.

2.1.1 Continuous Over-voltages

Continuous over-voltages are the results of the system operation under normal conditions. Although the power frequency voltage varies, it is accepted to be constant for the insulation coordination and design purposes. According to IEC 60071-2 [4], the over-voltage shape and limits are defined as

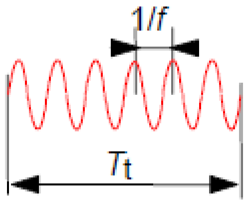

Figure 2.1: Continuous over-voltage shape [4]

$$f = 50 \text{ Hz or } 60 \text{ Hz}$$

$$T_t \geq 3600 \text{ s.}$$

2.1.2 Temporary (Sustained) Over-voltages

Temporary over-voltages occur as a result of earth faults, load disconnection, resonance, and asymmetric connection. They have relatively of smaller magnitude and longer duration compared to the other type of over-voltages. According to IEC 60071-2 [4], the over-voltage shape and limits are defined as

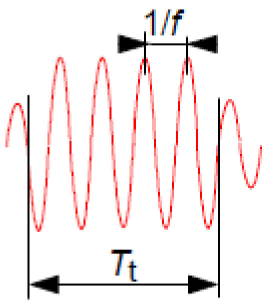

Figure 2.2: Temporary over-voltage shape [4]

$$10 \text{ Hz} < f < 500 \text{ Hz}$$

$$0.02 \text{ s} \leq T_t \leq 3600 \text{ s.}$$

Firstly, earth faults are the most common causes of temporary over-voltages. Over-voltage is caused between the healthy phase and ground. The magnitude of the over-voltage depends on the type of grounding such as isolated neutral grounding, resonant grounding, and direct grounding. Secondly, the disconnection of the load is another cause of temporary over-voltages. If the load is inductive and the short-circuit power of the network is small, the magnitude of the over-voltage increases. Also, it is worth to state that the magnitude of the short circuit power of a network shows its quality. If the short circuit power of a network is high, it is more durable to load disconnections. Furthermore, different states of the resonance situation may lead to temporary over-voltages. Resonance occurs when the reactance of the system becomes 0 due to the cancellation of the phasors of L and C components. During the resonance, high amplitude of the oscillations depending on the R, L, and C components causes over-voltages. Lastly, asymmetric connection in the system is considered to be one of the causes of temporary over-voltages. If the phases are not connected properly, or if the conductors are not solid, resonance may be produced at harmonic frequencies [5].

2.2 Transient Over-voltages

Transients in electrical systems are the sudden changes in the system conditions due to the switching actions or a fault occurrence in the network [6]. Transients are momentary events preceding the steady state conditions [7]. Although the duration of the transients is very short, they might result in a catastrophe in the system because of the eventual damages on the equipment. Transient over-voltages can be defined as the high voltage magnitude peaks with the fast-rising edges in high frequencies during the short transient duration [8]. There are different types of transient-over voltages in terms of both magnitude of the over-voltage and the duration of the transient event. They can be divided into 3 main subcategories as [4]

- Slow-front (switching) over-voltages
- Fast-front (lightning) over-voltages
- Very-fast-front over-voltages.

In this part, these over-voltage types and their standard characteristics will be explained and shapes of them will be shown. The main causes of that events will be clarified.

2.2.1 Slow-Front (Switching) Over-voltages

Slow-front over-voltages are caused mostly by the faults (line faults and short-circuiting of the busbar), load disconnection, no-load line voltage application and switching operations. They are heavily damped and of higher magnitude, and shorter duration compared to the temporary over-voltages [9]. Significant stress across switch-gear terminals may occur due to the switching actions. According to the network topology, the components used in the network and switch-gear preference, the magnitude of the over-voltage varies [5]. According to IEC 60071-2 [4], the over-voltage shape and limits are defined as

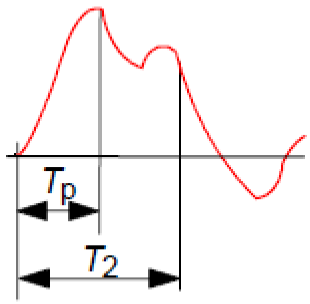

Figure 2.3: Slow-front over-voltage shape [4]

$$20\ \mu\text{s} < T_p \leq 5000\ \mu\text{s}$$

$$T_2 \leq 20\ ms.$$

First of all, the load connection such as the connection of a capacitor or connection of a motor causes oscillations in the system leading to slow-front over-voltages. Usually, 2 times higher peak voltage occurs compared to the nominal system voltage. Secondly, when the voltage is applied to an open-circuited line, a traveling wave is generated. A traveling wave doubles when it reflects from the open point leading to over-voltages of high magnitudes. Moreover, the disconnection of the load current, especially small inductive current, and capacitive current is one source of slow-front over-voltages. Due to the phase angle difference between current and voltage, opposite polarity between the terminals of the contact may occur, which causes a huge voltage magnitude. The highest voltage occurs when the current is capacitive [5], [6].

2.2.2 Fast-Front (Lightning) Over-voltages

Fast-front over-voltages occur as a result of a meteorological process called lightning. They are of higher magnitude and shorter duration compared to slow-front over-voltages and temporary over-voltages. According to IEC 60071-2 [4], the over-voltage shape and limits are defined as in Figure 2.4 on the next page.

Lightning can induce over-voltage on the system in different ways by a direct stroke to the conductors or via back flashover from the grounded components. The details of the lightning phenomenon, standard impulse test voltage and current of the lightning will be discussed in the next chapters in detail as lightning is the main scope of this study.

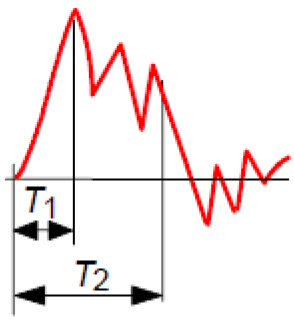

Figure 2.4: Fast-front over-voltage shape [4]

$$0.1\ \mu\text{s} < T_1 \leq 20\ \mu\text{s}$$

$$T_2 \leq 300\ \mu\text{s}.$$

2.2.3 Very-Fast-Front Over-voltages

Very-fast-front over-voltages occur while opening a disconnector in the system because of the arc interruption restriking occurrence. They are of the shortest duration among the whole over-voltage types. These over-voltages are important for the equipment which is very close to the opened disconnector [5], [6]. According to IEC 60071-2 [4], the over-voltage shape and limits are defined as

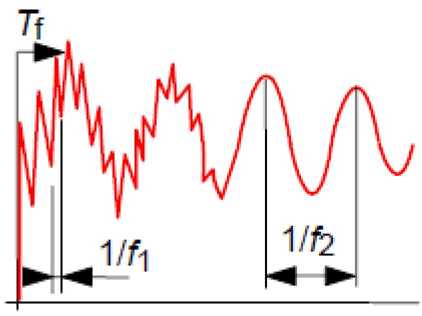

Figure 2.5: Very-fast-front over-voltage shape [4]

$$T_f \leq 100\ ns$$

$$0.3\ M\text{Hz} < f_1 < 100\ M\text{Hz}$$

$$30\ k\text{Hz} < f_2 < 300\ k\text{Hz}.$$

2.3 Lightning

Lightning occurs as an electrostatic discharge during the meteorological processes (mostly thunderstorms), if the breakdown strength of the air is exceeded. The lightning discharges can be categorized into 3 main parts as intracloud lightning, cloud-to-cloud lightning, and cloud-to-ground lightning. From power system point of view, cloud-to-ground lightning is considered more [10].

The thunder clouds in the atmosphere have different types of charges for the different temperatures. In the lower parts of the cloud, negative charges are located in the regions where the temperature is around -5°C. Also, in the lower parts of the cloud, there are some local regions having positive charges where the temperature is around 0°C. In the higher parts of the cloud, positive charges are located in the regions where the temperature is around -20°C [11]. The charge distribution of a cloud above a high voltage transmission line can be illustrated as in Figure 2.6.

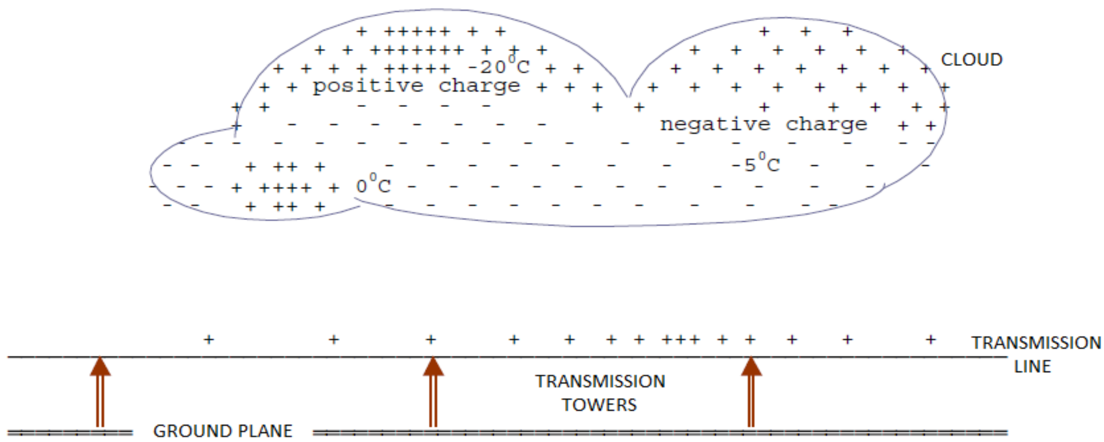

Figure 2.6: Induced charges in the cloud above a transmission line [11].

If the electric field in the vicinity of the negative charge centers reaches up to 10 kV/cm, a streamer is formed due to the elongation of the large water drops. It propagates from cloud to ground with a fast velocity which is around one-tenth of the speed of the light. This streamer is usually extinguished after a short distance from the cloud. Just after the first streamer, a second streamer emerges which follows the path of the first streamer. Similar to the first one, it is also extinguished after a while by leading to the emergence of new streamers which will follow the same main path. This process occurs for several times by causing an increase in the channel length by 10 to 200 m. This process is called as stepped leader stroke.

When the stepped leader is close enough to the ground (15 to 50 m), the increased intensity in the ground causes an upward streamer that bridges with the other streamer. Along the ionized path, a large neutralizing current that is produced by the stepped leader flows for the charge neutralization. This current flow is called as return stroke. Return strokes carry 20 kA as an average; however, it can reach till 200 kA. Subsequent strokes may be formed from the other negatively charged areas in the cloud that use the same ionized path [11]. Based on these processes, propagation of the lightning channel can be illustrated as in Figure 2.7.

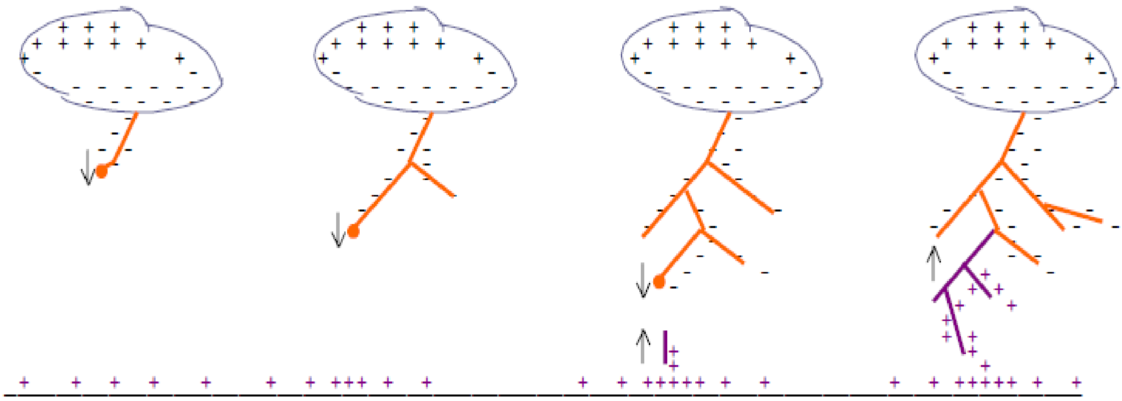

Figure 2.7: Propagation of the lightning channel [11].

2.3.1 Direct Stroke

When the lightning strikes directly to any part of the electrical network, it is defined as direct stroke [2]. As a result of this stroke, travelling waves are generated, which travel along the line. These travelling waves are often affected by the insulator between the phase conductors and cross-arm of the tower. When the voltage is of high magnitude, short circuit is caused in the system due to flash over of the insulator [12].

When the lightning strikes to the phase conductor directly, it causes lightning current to be divided into two equal halves traveling to the opposite directions. The mathematical expression for the traveling waves as a result of this separation can be shown as follows:

$$U = \frac{1}{2} \cdot Z_0 \cdot I. \tag{2.1}$$

As can be seen from Equation 2.1, the relationship between the voltage and current is determined by surge impedance, where the surge impedance is

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}. \tag{2.2}$$

Equation 2.2 shows that the magnitude of the surge impedance and thereby current is determined by the line parameters. In Finnish networks, surge impedance is typically between 250 Ω and 500 Ω [13].

2.3.2 Indirect Stroke

If the lightning hits to the grounded parts of the power system, it may cause an indirect stroke [2]. This traveling wave travels back and forth along the tower and is reflected at the footing and top of the tower causing a rise in the voltage and stress on the insulators. When the withstand level of the insulator is exceeded, insulator flashes over. This type of flashover is called as back flashover [12]. The probability of back flashover is high if the grounding of the system is poor or the lightning current is very high [5].

2.3.3 Standard Lightning Impulse Test Voltage and Current

In power systems, for the test of the equipment against lightning, standard waveforms defined by IEC are used. According to IEC 60060-1 [14] and IEC 61000-4-5 [15], those waveforms are defined by front time and time to half value with margin limits. Before giving the standard waveforms, the terms related to the waveforms will be explained.

Front Time : The time difference between the virtual origin and peak point.

Time to Half Value : The time difference between the virtual origin and the point where the impulse is 50% of the peak value.

The standard test voltage defined by IEC 60060-1 [14] is shown in Figure 2.8.

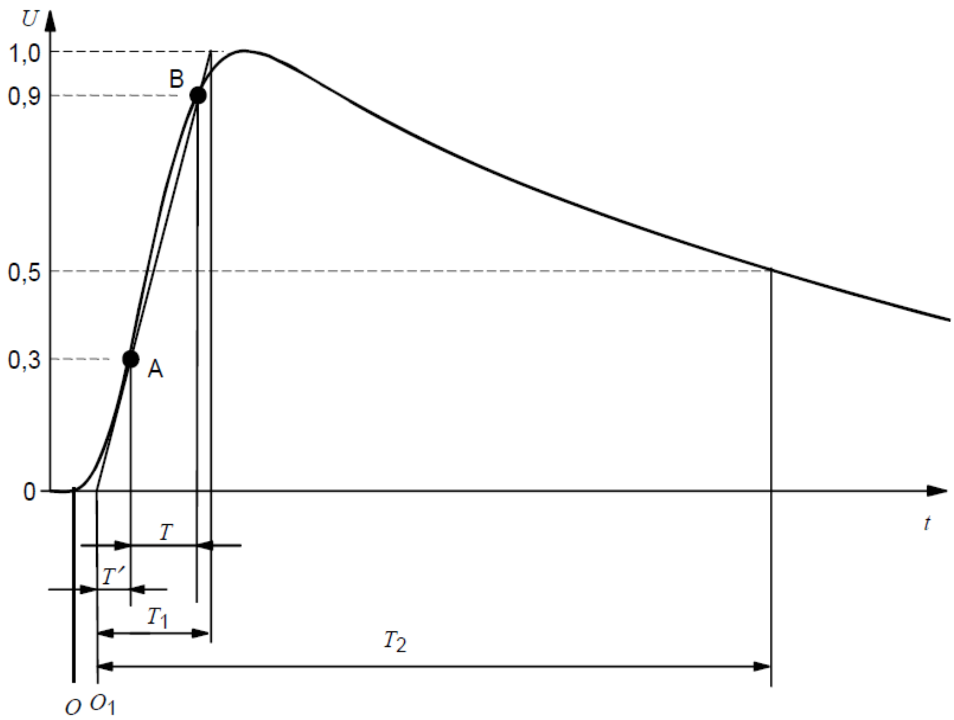

Figure 2.8: Standard lightning impulse test voltage [14].

Origin is shown as O and virtual origin is shown as O_1 in Figure 2.8. Origin is the point where the voltage value becomes nonzero. Virtual origin is the beginning point of the line drawn from point A $(0.3 \cdot T_1)$ to point B $(0.9 \cdot T_1)$. Also, T is defined as the time duration between points A and B. Limits with the margins defined by the standard are as follows:

$$T = 0.6 \cdot T_1 = 2 \cdot T'$$
$$T_1 = 1.2 \ \mu\text{s} \pm 30\%$$
$$T_2 = 50 \ \mu\text{s} \pm 20\%.$$

Due to the limits given above, the above waveform is defined as 1.2/50 μs test voltage. The standard test current defined by IEC 61000-4-5 [15] is shown in Figure 2.9.

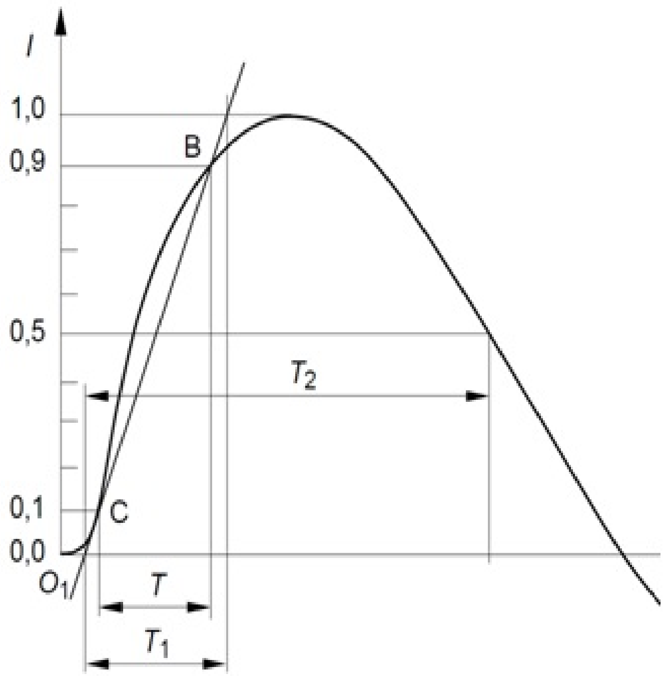

Figure 2.9: Standard lightning impulse test current [15].

Limits with the margins defined by the standard are as follows:

$$T = 0.8 \cdot T_1$$
$$T_1 = 8 \ \mu\text{s} \pm 20\%$$
$$T_2 = 20 \ \mu\text{s} \pm 20\%.$$

Due to the limits given above, the above waveform is defined as 8/20 μs test current.

2.4 Over-voltage Protection

2.4.1 Surge Arrester

Surge arresters are protective devices that protect the other important equipment in the system against internal or external over-voltages. Surge arresters operate according to their V-I characteristics, which are nonlinear. The most important element of the surge arrester is metal oxide varistor that is nonlinearly characterized [16].

When the surge arrester is operating under normal conditions, it conducts a very small current. On the other hand, when the surge arrester is exposed to the over-voltages, it conducts a high current to flow over-voltage charges to the ground. After mitigating the over-voltage, the surge arrester returns to its normal state. If the surge arrester is exposed to a high amount of energy, it might be damaged [2].

2.4.2 Spark Gap

Spark gaps are protective devices used against the high voltage surges in power systems. A spark gap consists of two electrodes. One of the electrodes is connected to the device which is protected, and the other electrode is connected to the ground. The gap between electrodes is usually filled with a gas or air. When a surge comes, the spark gap tries to mitigate the surge across the protected equipment by flowing it to ground. However, the operation of the gap may cause earth faults in the systems that do not have fast re-closing. Also, due to the weather conditions, the spark gap might be damaged [5].

2.4.3 Surge Capacitor

Surge capacitances are used to reduce the steepness of the wavefront of the surges. A surge capacitance is placed parallel to the equipment that is tried to be protected. In case of a surge occurrence, the current flows through the capacitor by charging it, which lowers the intensity of the surge voltage. The effectiveness of the capacitor is determined by the amount of energy that it can absorb depend upon its capacitance and size. As the energy absorbed by the surge capacitance is limited, it is more effective against voltage surges of short duration. One of the advantages of the surge capacitance is that there is no time delay during the operation of the surge capacitance because it always conducts some current even if it is not exposed to any surge. On the other hand, due to the current limit it can handle, there should be a surge arrester placed to protect the surge capacitance from intense surges [6], [17].

3 Modeling of the System

In this part, the modeling of each part of the system will be given in detail. Before the models, single line diagrams of the NPPs will be shown and explained. Then, the modeling of each part will be clarified based on the single line diagrams.

Single line diagram of the first NPP is demonstrated in Figure 3.1.

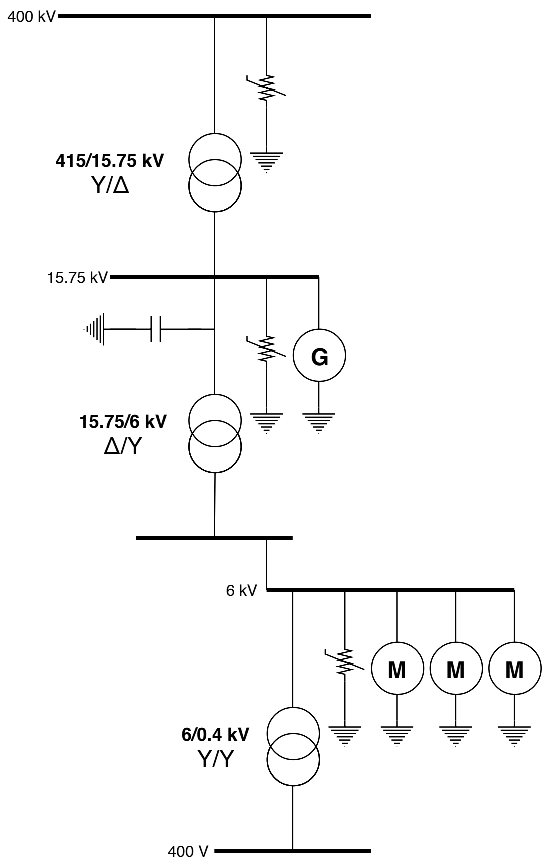

Figure 3.1: Single line diagram of the first NPP.

In the first NPP, there are 4 voltage levels as 400 kV, 15.75 kV, 6 kV, and 400 V. There are transformers between each level. There is a generator in 15.75 kV level and motors in 6 kV level. The transformers, generator, and motors are protected by surge arresters in 400 kV, 15.75 kV, and 6 kV levels. Also, there is a surge capacitance in 15.75 kV level to mitigate the possible over-voltages. To study the over-voltages induced by the lightning stroke to the transmission towers, a lightning source, 4 transmission towers, and overhead lines between towers have been modeled. 415/15.75 kV, 15.75/6 kV, and 6/0.4 kV transformers have been modeled. One surge arrester for each phase of 400 kV, 15.75 kV, and 6 kV levels has been selected and modeled properly.

Single line diagram of the second NPP is demonstrated in Figure 3.2.

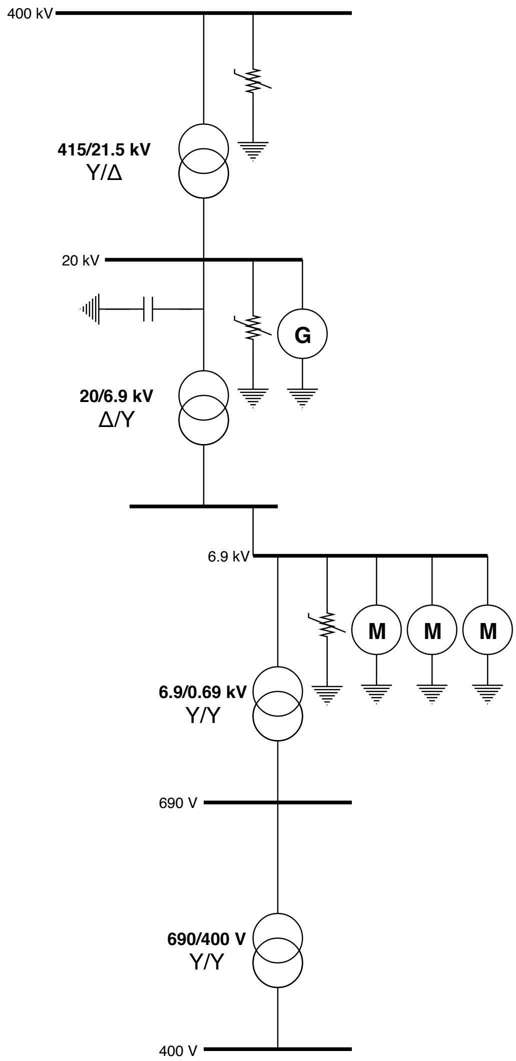

Figure 3.2: Single line diagram of the second NPP.

In the second NPP, there are 5 voltage levels as 400 kV, 20 kV, 6.9 kV, 690 V, and 400 V. There are transformers between each level. There is a generator in 20 kV level and motors in 6.9 kV level. The transformers, generator, and motors are protected by surge arresters in 400 kV, 20 kV, and 6.9 kV levels. Also, there is a surge capacitance in 20 kV level to mitigate the possible over-voltages. To study the over-voltages induced by the lightning stroke to the transmission towers, a lightning source, 4 transmission towers and overhead lines between towers have been modeled. 415/21.5 kV, 20/6.9 kV, 6.9/0.69 kV, and 690/400 V transformers been modeled. One surge arrester for each phase of 400 kV, 20 kV, and 6.9 kV levels has been selected and modeled properly.

While modeling the parts of NPPs, same lightning source model, tranmission tower models, overhead line models, and surge arrester models have been used for both NPPs. Each model from that category will be explained once in subsections. However, for power transformers, there are differences while calculating the parameters. Therefore, power transformer models of each NPP will be given in different subsections.

3.1 Modeling of Lightning Source

The lightning source has been modeled as a current source with a parallel resistance of 400 Ω [18]. This parallel resistance stands for the lightning path impedance. The magnitude of the current source has been adjusted as 200 kA and 20 kA for different studies. For a direct stroke to the ground wire of the tower, 200 kA has been used, and for a direct stroke to the phase conductors, 20 kA has been used. Parameters of front and tail time were determined according to IEC 60060-1 standards as 1.2/50 μs [14]. The model can be represented in Figure 3.3.

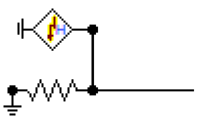

Figure 3.3: Lightning source model.

3.2 Modeling of Transmission Towers

After the electricity is generated in the plant by generators, it is stepped-up via a transformer to the transmission voltage level. In Finland, the voltage level of the transmission is 400 kV [19]. This stepped-up voltage is transmitted to the primary transformers via overhead lines and transmission towers. When the lightning strikes to the transmission tower, it creates a traveling wave that travels to the other parts of the tower by affecting the induced voltage of the other parts of the system. Therefore, a proper implementation of the tower model is important for this study. Different number of towers has been simulated to see the effect of tower number. The configuration of 400 kV double circuit has been used for the model [13]. The dimensions and the design of the tower can be seen in Figure 3.4.

In Figure 3.4,

H1: Maximum permissible ground clearance (m)

H2: Maximum sag (m)

H3: Vertical spacing between conductors (m)

H4: Vertical clearance between ground wire and top conductor (m) [20].

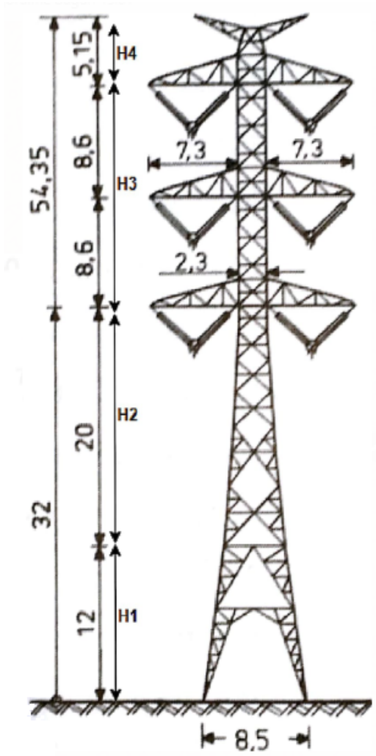

Figure 3.4: 400 kV double circuit transmission tower in Finland [13].

By using the dimensions of the tower and some coefficients, a transmission tower can be modeled as in Figure 3.5 [21].

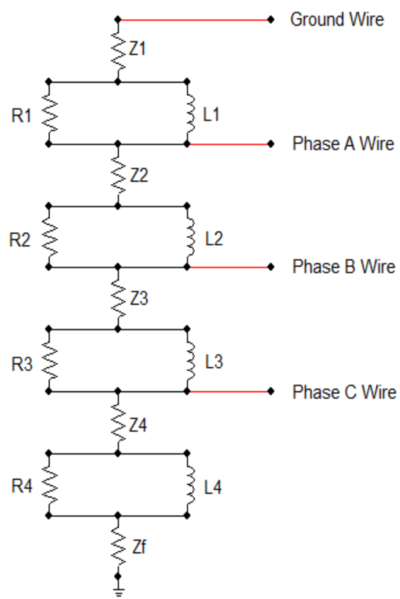

Figure 3.5: Transmission tower modeling.

According to [22], [23], Z_1, Z_2, Z_3, and Z_4 parameters in Figure 3.5 are calculated by using the below formula:

$$Z_{\mathrm{t}} = 60 \cdot ln\left(\sqrt{2} \cdot \frac{2h}{R}\right) - 60. \tag{3.1}$$

This formula is used when the tower is cylindrical. "h" stands for the height of the part, "R" stands for the radius of the part. At this point, each part has been assumed as cylindrical. While calculating Z_3 average of 2.3 and 8.5 is taken as diameter, and for Z_4, 8.5 is taken as average. The results of the calculations for the impedances are shown in Table 3.1.

Table 3.1: Results of the impedance calculations for the transmission tower model.

Impedances	**Values**
Z_1	155 Ω
Z_2	123.1 Ω
Z_3	123.1 Ω
Z_4	123.51 Ω

The resistances and inductances of the model have been calculated as follows [21]:

$$R_{\mathrm{i}} = \frac{-2 \cdot Z_{\mathrm{i}} \cdot ln\alpha}{H_1 + H_2 + H_3} \cdot H_{\mathrm{i}} \tag{3.2}$$

$$R_4 = -2 \cdot Z_4 \cdot ln\alpha \tag{3.3}$$

$$L_{\mathrm{i}} = \alpha \cdot R_{\mathrm{i}} \frac{2 \cdot H}{C_0}. \tag{3.4}$$

In above formulas, "α" is attenuation coefficient and taken as 0.89. "C_0" is the propagation velocity and taken as $3 \cdot 10^8$ m/s. According to the formulas above, the resistances and inductances have been found as in Table 3.2.

Table 3.2: Results of the resistance and inductance calculations .

Resistances	**Values**	**Inductances**	**Values**
R_1	5.248 Ω	L_1	1.69 H
R_2	11.67 Ω	L_2	3.76 H
R_3	10.03 Ω	L_3	3.23 H
R_4	28.78 Ω	L_4	9.28 H

Also, according to [13], the footing resistance Z_{f} is taken as 30 Ω.

3.3 Modeling of Overhead Lines

Overhead lines have impacts on the lightning induced over-voltage studies as their capacitance, inductance, and resistance values affect the equivalent impedance of the system. Therefore, the modeling of overhead lines should be done properly. In ATPDraw, lumped, distributed, and LCC models are available for modeling. Although LCC models give more detailed analysis, several data of tower dimensions and bundling types are needed. As there is no detailed information about that data, a lumped model has been used. RLC PI equivalent model in ATPDraw has been chosen as the lumped model. PI equivalent model consists of R, L, and C data of the line, and can be represented as in Figure 3.6.

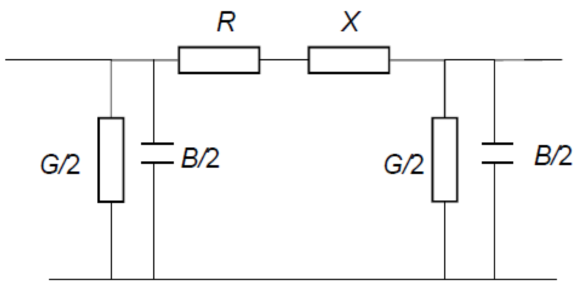

Figure 3.6: PI equivalent model of a transmission line [24].

In Finland, for 400 kV level of transmission, one of the most preferred overhead line is “400 kV 2*Finch”. The data for this overhead line is as in Table 3.3 [24].

Table 3.3: Data of “400 kV 2*Finch” overhead line for PI equivalent model [24].

$r(\Omega/\text{km})$	$x(\Omega/\text{km})$	b (S/km)	$g(\mu S/\text{km})$	Z_0 (Ω)
0.026	0.33	$3.58\ 10^{-6}$	0.022	304

In ATPDraw software, $R(\Omega/\text{m})$, $L(mH/\text{m})$, and $C(\mu F/\text{m})$ data is required with the length of the line (m). $R(\Omega/\text{m})$ has been taken from the above table, and $L(mH/\text{m})$ and $C(\mu F/\text{m})$ have been calculated from $b(S/\text{km})$ and $g(\mu S/\text{km})$ parameters of the table. The distance between the towers has been taken as 250 m and line length has been chosen accordingly.

$$L = \frac{x}{\omega} = \frac{0.33}{2\pi \cdot 50} = 1.05 \cdot 10^{-3}\ H/\text{km}$$

$$C = \frac{b}{\omega} = \frac{3.58 \cdot 10^{-6}}{2\pi \cdot 50} = 1.139 \cdot 10^{-2}\ \mu F/\text{km}$$

Therefore, the parameters entered in ATPDraw software are presented in Table 3.4.

Table 3.4: Overhead line parameters used in ATPDraw.

$R(\Omega/\text{m})$	$L(mH/\text{m})$	$C(\mu F/\text{m})$	Length(m)
$2.6{\cdot}10^{-5}$	$1.05{\cdot}10^{-3}$	$1.139{\cdot}10^{-5}$	250

3.4 Modeling of 415/15.75 kV Transformer

For this work, modeling of 415/15.75 kV transformer is one of the most important models among the system parts. Since the lightning induced over-voltages are investigated in this study, the transformer should be modeled properly for the feasible transfer of over-voltage to the secondary side. The transformer consists of capacitive and inductive elements which make the transformer frequency dependent. Therefore, the model of the transformer for high frequencies is needed.

Transformers can be designed with 2 possible methods in terms of frequency behaviors. In the first method, capacitance and reactance values of the model are calculated according to the mechanical description of the transformer. However, due to the lack of information about the mechanical description and difficulties to calculate the parameters make this type of modeling inapplicable. In the second method, the calculation of the parameters is based on FRA of the transformer. According to the results of FRA, capacitance and inductance values are calculated for different frequencies by using transfer functions [25]. In this thesis, the second method has been used to model 415/15.75 kV and 415/21.5 kV transformers.

According to [26], the following model in Figure 3.7 has been proposed for high-frequency transformer:

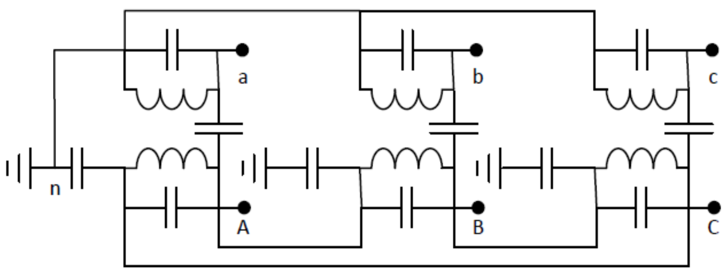

Figure 3.7: Structure of the 415/15.75 kV transformer proposed model [26].

This model consists of L and C components. For this model, it should be considered that an inductor behave as an open circuit for very high frequencies. Therefore, the model is dominated by capacitive components in high frequencies. It means that the induced voltage on the secondary side of the transformer is determined by the capacitive division ratio between the primary and secondary sides. Thus, in this model, the components shown in Figure 3.7 have been calculated from FRA meticulously, and then tuned to have more reasonable results.

The model consists of primary side capacitance and inductance, secondary side capacitance and inductance, a capacitance between the primary side and the secondary side, and a stray capacitance transferred to the secondary side. Those components have been calculated by using FRA. FRA data of 415/15.75 kV transformer is given in Appendix A. The detailed approach for the calculations will be given in this part.

Before going through the calculations, it should be mentioned that end to end measurement setup has been assumed for FRA. The setup can be shown in Figure 3.8. The source is connected to the primary side with a reference channel and a measurement channel is connected to the secondary side. Also, the measurement impedance has been taken as 50 Ω for the calculations.

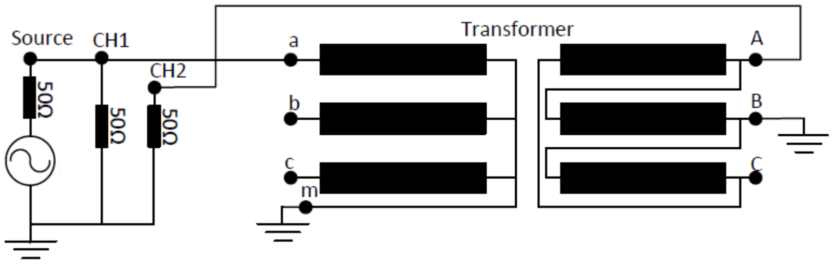

Figure 3.8: End to end test setup [26].

In FRA data, magnitude and phase angle plot of the analysis exist. The magnitude for FRA is given in dB, and the phase angle is given in degrees (°). Therefore, the magnitude should be converted from dB as below:

$$|FRA|_{\mathrm{dB}} = 20\log\left|\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right| \tag{3.5}$$

$$\left|\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right| = 10^{\frac{|FRA|_{\mathrm{dB}}}{20}}. \tag{3.6}$$

Also, the phase angle expression is as follows:

$$\angle FRA = \angle\left(\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right)^{\circ}. \tag{3.7}$$

From end to end measurements, the ratio between output voltage and input voltage can be found as

$$\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}} = \frac{50}{50+Z_{\mathrm{Tr}}} \tag{3.8}$$

where

$$\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}} = \left|\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right|\angle\left(\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right)^{\circ}. \tag{3.9}$$

Z_{Tr} is the coil impedance of the transformer in Equation 3.8. The formula in Equation 3.8 can be modified to express Z_{Tr} as

$$Z_{\mathrm{Tr}} = 50\left(\frac{1}{\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}} - 1\right) \tag{3.10}$$

$$Z_{\mathrm{Tr}} = 50\left(\frac{1 - \frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}}{\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}}\right). \tag{3.11}$$

From Z_{Tr}, the inductance is calculated by dividing the imaginary part with the angular speed as

$$L = \frac{x}{\omega}. \tag{3.12}$$

From Z_{Tr}, te capacitance is calculated by diving 1 with the multiplication of angular speed with the imaginary part as

$$C = \frac{1}{x \cdot \omega}. \tag{3.13}$$

From now on, parameter calculations of the model will be given in detail. It should be noted that, this transformer has been assumed to be balanced, and calculations have been made for only one phases of the each side.

3.4.1 HV Side Calculations

The calculations have been done by using FRA of HV side. HV side inductance and capacitance calculations will be given in this part.

HV Side Inductances

In FRA, it can be observed that till 300-400 Hz, the behaviour of the transformer is inductive as the impedance is increasing due to increase in transfer function. 20 Hz value has been chosen from linear zone to calculate L_{H} which is HV side inductance. For 20 Hz, the data from FRA is as follows:

$$\left|\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right|_{\mathrm{dB}} = -40\,\mathrm{dB} \quad , \quad \angle\left(\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right)^{\circ} = \angle{-90^{\circ}}.$$

With the above values, Z_{Tr} is calculated by using Equations 3.9 and 3.10:

$$Z_{\mathrm{Tr}} = -50 + j5000\ \Omega.$$

From Z_{Tr}, the inductance is calculated by using Equation 3.12 as

$$L_{\mathrm{H}} = 39.79\ H.$$

This inductance can be used for the phases in HV side as

$$L_{\mathrm{A}} = L_{\mathrm{B}} = L_{\mathrm{C}} = 39.79\ H.$$

HV Side Capacitances

In FRA, it can be observed that between 400 and 6000 Hz, the behaviour of the transformer is capacitive as the impedance is decreasing due to decrease in transfer function. 2000 Hz value has been chosen from linear zone to calculate C_{H} which is HV side capacitance. For 2000 Hz, the data from FRA is as follows:

$$\left|\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right|_{\mathrm{dB}} = -50\ \mathrm{dB} \quad , \quad \angle\left(\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right)^{\circ} = \angle 90^{\circ}.$$

With the above values, Z_{Tr} is calculated by using Equations 3.9 and 3.10:

$$Z_{\mathrm{Tr}} = -50 - j15811.39\ \Omega.$$

From Z_{Tr}, the capacitance is calculated by using Equation 3.13 as

$$C_{\mathrm{H}} = 5.033\ nF.$$

This capacitance can be used for the phases in HV side as

$$C_{\mathrm{A}} = C_{\mathrm{B}} = C_{\mathrm{C}} = 5.033\ nF.$$

3.4.2 LV Side Calculations

The calculations have been done by using FRA of LV side. LV side inductance and capacitance calculations will be given in this part.

LV Side Inductances

In FRA, it can be observed that till 300-400 Hz, the behaviour of the transformer is inductive as the impedance is increasing due to increase in transfer function. 20 Hz value has been chosen from linear zone to calculate L_{L} which is LV side inductance. For 20 Hz, the data from FRA is as follows:

$$\left|\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right|_{\mathrm{dB}} = -2\ \mathrm{dB} \quad , \quad \angle\left(\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right)^{\circ} = \angle -35^{\circ}.$$

With the above values, Z_{Tr} is calculated by using Equations 3.9 and 3.10:

$$Z_{\mathrm{Tr}} = 1.562 + j36.105\ \Omega.$$

From Z_{Tr}, the inductance is calculated by using Equation 3.12 as

$$L_{\mathrm{L}} = 0.28758\ H.$$

This inductance can be used between the phases in LV side as

$$L_{\mathrm{ab}} = L_{\mathrm{bc}} = L_{\mathrm{ca}} = 0.28758\ H.$$

LV Side Capacitances

In FRA, it can be observed that between 400 and 6000 Hz, the behaviour of the transformer is capacitive as the impedance is decreasing due to decrease in transfer function. 2000 Hz value has been chosen from linear zone to calculate C_{L} which is LV side capacitance. For 2000 Hz, the data from FRA is as follows:

$$\left|\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right|_{\mathrm{dB}} = -4 \text{ dB} \quad , \quad \angle\left(\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right)^{\circ} = \angle 40^{\circ}.$$

With the above values, Z_{Tr} is calculated by using Equations 3.9 and 3.10:

$$Z_{\mathrm{Tr}} = 10.7 - j50.937\ \Omega.$$

From Z_{Tr}, the capacitance is calculated by using Equation 3.13 as

$$C_{\mathrm{L}} = 1.529\ \mu F.$$

This capacitance can be used between the phases in LV side as

$$C_{\mathrm{ab}} = C_{\mathrm{bc}} = C_{\mathrm{ca}} = 1.529\ \mu F.$$

3.4.3 Capacitive Coupling Calculations Between HV and LV Sides

The calculations have been done by using FRA between HV and LV sides. Calculations to calculate the capacitance representing the capacitive coupling between HV and LV sides will be given in this part. In FRA, it can be observed that till 200 Hz, the behaviour of the transformer is capacitive as the impedance is decreasing due to decrease in transfer function. 200 Hz value has been chosen from linear zone to calculate C_{HL} which is the capacitance between HV and LV sides. For 200 Hz, the data from FRA is as follows:

$$\left|\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right|_{\mathrm{dB}} = -85 \text{ dB} \quad , \quad \angle\left(\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right)^{\circ} = \angle 90^{\circ}.$$

With the above values, Z_{Tr} is calculated by using Equations 3.9 and 3.10:

$$Z_{\mathrm{Tr}} = 50 - j889139.705\ \Omega.$$

From Z_{Tr}, the capacitance is calculated by using Equation 3.13 as

$$C_{\mathrm{HL}} = 8.95\ nF.$$

This capacitance can be used between HV and LV sides of each phase as

$$C_{\mathrm{Aa}} = C_{\mathrm{Bb}} = C_{\mathrm{Cc}} = 8.95\ nF.$$

3.4.4 Stray Capacitance Calculations

Although the effect of stray capacitance is visible in FRA of LV side for the regions having sudden changes, it is not possible to calculate the exact value from FRA because any point in the distorted region leads to very different values. To be in the safe side, stray capacitance value has been estimated according to the ratio between the primary and secondary sides of the transformer.

In high frequency, the inductive components behave as an open circuit, and only capacitive components dominate the system. Basically, the ratio of induced voltage from HV side to LV side of the transformer will be determined by the ratio between capacitive components that are the capacitance between HV and LV sides, the capacitance of LV side, and stray capacitance. Therefore, stray capacitance value has been chosen during the simulations to have a reasonable ratio between capacitive components. The chosen stray capacitance value is

$$C_{\mathrm{S}} = 3.4 \cdot 10^{-7} \ F.$$

This capacitance can be used for all phases as

$$C_{\mathrm{Sa}} = C_{\mathrm{Sb}} = C_{\mathrm{Sc}} = 3.4 \cdot 10^{-7} \ F.$$

After calculating each parameter, all of them can be shown in Table 3.5.

Table 3.5: Calculated parameters for 415/15.75 kV transformer.

Parameters	**Values**	**Parameters**	**Values**
L_{A}	39.79 H	C_{ab}	1.529 μF
L_{B}	39.79 H	C_{bc}	1.529 μF
L_{C}	39.79 H	C_{ca}	1.529 μF
L_{ab}	0.28758 H	C_{Aa}	8.95 nF
L_{bc}	0.28758 H	C_{Bb}	8.95 nF
L_{ca}	0.28758 H	C_{Cc}	8.95 nF
C_{A}	5.033 nF	C_{Sa}	$3.4{\cdot}10^{-1}$ μF
C_{B}	5.033 nF	C_{Sb}	$3.4{\cdot}10^{-1}$ μF
C_{C}	5.033 nF	C_{Sc}	$3.4{\cdot}10^{-1}$ μF

The transformer has been assumed to be balanced, and all the parameters above have been used for each phase. The resulted simulation model for 415/15.75 kV transformer for ATPDraw can be demonstrated in Figure 3.9.

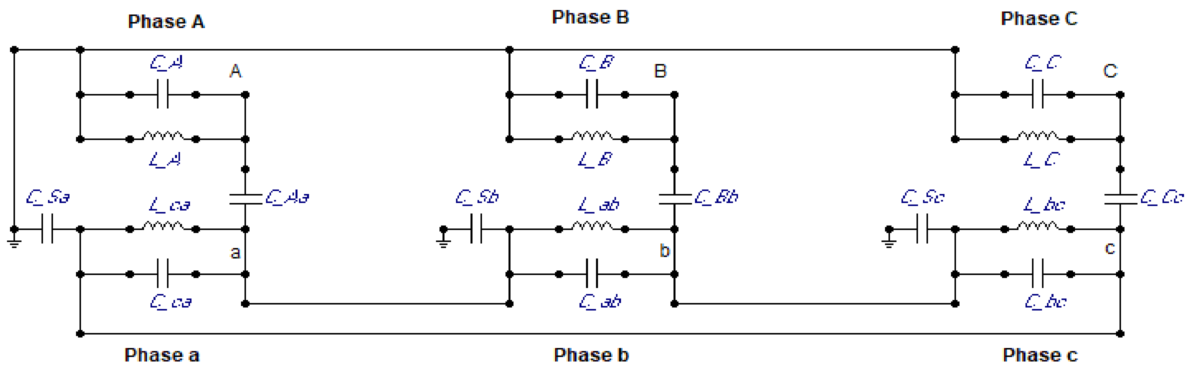

Figure 3.9: Simulation model for 415/15.75 kV transformer in ATPDraw.

3.5 Modeling of 15.75/6 kV and 6/0.4 kV Transformers

In order to mdodel 15.75/6 kV and 6/0.4 kV transformers of the first NPP, the proposed model for the medium voltage distribution systems in the doctoral dissertation of Nehmdoh Sabiha [2] has been used. The model has been developed is based on two-port network theory. Computation of the parameters has been done by open circuiting the input and output ports. By taking the first and the second resonance frequencies into account, the impedance parameter calculations have been done for varying frequencies. The experimental and simulated results in that dissertation are consistent with each other. Also, the model can be used for both loaded and unloaded situations. Ohe phase of the model implemented in ATPDraw software can be shown in Figure 3.10.

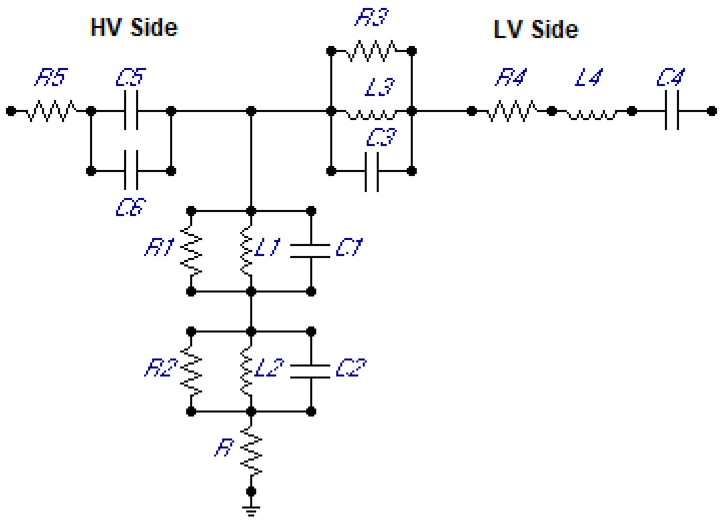

Figure 3.10: One phase of the simulation model for 15.75/6 kV and 6/0.4 kV transformers in ATPDraw.

The parameters of the simulation model in Figure 3.10 are as follows [2]:

Table 3.6: Parameters of 15.75/6 kV and 6/0.4 kV transformers.

Parameters	**Values**
R_1	400 Ω
R_2	558.5405 Ω
R_3	1000 Ω
R_4	10^{-6} Ω
R_5	50 Ω
R	1500 Ω
L_1	0.00856 mH
L_2	0.0046 mH
L_3	0.036897 mH
L_4	0.0428296 mH
C_1	0.021063 μF
C_2	0.00302967 μF
C_3	0.00512 μF
C_4	0.00022167 μF
C_5	0.0004221 μF
C_6	0.00019152 μF

3.6 Modeling of 415/21.5 kV Transformer

To model 415/21.5 kV transformer, the same approach to model 415/15.75 kV transformer has been used. Parameters of the transformer have been calculated by using FRA data of this transformer which will be given in Appendix B. From now on, the calculations of the model parameters will be explained.

3.6.1 HV Side Calculations

The calculations have been done by using FRA of HV side. The inductances and capacitances of A-N, B-N, and C-N calculated separately. The approach and calculations will be given in this part.

HV Side Inductances

In FRA of A-N, it can be observed that till 400-500 Hz, the behaviour of the transformer is inductive as the impedance is increasing due to increase in transfer function. 90 Hz value has been chosen from linear zone to calculate L_{A} which is HV side inductance of Phase A. For 90 Hz, the data from FRA is as follows:

$$\left|\frac{V_{out}}{V_{in}}\right|_{\mathrm{dB}} = -50\,\mathrm{dB} \quad , \quad \angle\left(\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right)^{\circ} = \angle{-90^{\circ}}.$$

With the above values, Z_{Tr} is calculated by using Equations 3.9 and 3.10:

$$Z_{Tr} = -50 + j15811\ \Omega.$$

From Z_{Tr}, the inductance is calculated by using Equation 3.12 as

$$L_{\mathrm{A}} = 27.96\ H.$$

To find L_{B}, 65 Hz value has been chosen from linear zone of FRA of B-N. For 65 Hz, the data from FRA of B-N is the same as the data in FRA of A-N. Therefore, Z_{Tr} values are the same. From Z_{Tr}, L_{B} is calculated by using 3.12 as

$$L_{\mathrm{B}} = 38.7\ H.$$

To find L_{C}, 80 Hz value has been chosen from linear zone of FRA. For 80 Hz, the data from FRA of C-N is the same as the data in FRA of A-N and FRA of B-N. Therefore, Z_{Tr} values are the same. From Z_{Tr}, L_{C} is calculated by using Equation 3.12 as

$$L_{\mathrm{C}} = 31.45\ H.$$

HV Side Capacitances

In FRA of A-N, it can be observed that between 500 and 3000 Hz, the behaviour of the transformer is capacitive as the impedance is decreasing due to decrease in transfer function. 1100 Hz value has been chosen from linear zone to calculate C_{A} which is HV side capacitance of Phase A. For 1100 Hz, the data from FRA is as follows:

$$\left|\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right|_{\mathrm{dB}} = -50\ \mathrm{dB} \quad , \quad \angle\left(\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right)^{\circ} = \angle 90^{\circ}.$$

With the above values, Z_{Tr} is calculated by using Equations 3.9 and 3.10:

$$Z_{\mathrm{Tr}} = -50 - j15811.39\ \Omega.$$

From Z_{Tr}, the capacitance is calculated by using Equation 3.13 as

$$C_{\mathrm{A}} = 9.16\ nF.$$

As the values from FRA of B-N and C-N are the same as A-N in the defined interval, C_{B} and C_{C} values are the same as C_{A}. Therefore,

$$C_{\mathrm{B}} = C_{\mathrm{C}} = 9.16\ nF.$$

3.6.2 LV Side Calculations

The calculations have been done by using FRA of LV side. The inductances and the capacitances between the phases have been calculated separately. The approach and the calculations will be given in this part.

LV Side Inductances

In FRA of a-b, it can be observed that till 300-400 Hz, the behaviour of the transformer is inductive as the impedance is increasing due to increase in transfer function. 50 Hz value has been chosen from linear zone to calculate $L_{\text{a-b}}$ which is LV side inductance between the Phases A and B. For 50 Hz, the data from FRA is as follows:

$$\left|\frac{V_{out}}{V_{in}}\right|_{\text{dB}} = -10\,\text{dB} \quad , \quad \angle\left(\frac{V_{\text{out}}}{V_{\text{in}}}\right)^{\circ} = \angle{-67^{\circ}}.$$

With the above values, Z_{Tr} is calculated by using Equations 3.9 and 3.10:

$$Z_{\text{Tr}} = -11.78 + j145.54\ \Omega.$$

From Z_{Tr}, the inductance is calculated by using Equation 3.12 as

$$L_{\text{ab}} = 0.4633\ H.$$

To find $L_{\text{b-c}}$, 90 Hz value has been chosen from linear zone of FRA of b-c. For 90 Hz, the data from FRA of b-c is the same as the data in FRA of a-b. Therefore, Z_{Tr} values are the same. From Z_{Tr}, $L_{\text{b-c}}$ is calculated by using Equation 3.12 as

$$L_{\text{bc}} = 0.257\ H.$$

FRA of b-c and FRA of c-a are the same. Therefore,

$$L_{\text{ca}} = L_{\text{bc}} = 0.257\ H.$$

LV Side Capacitances

In FRA of a-b, it can be observed that between 400 and 3000 Hz, the behaviour of the transformer is capacitive as the impedance is decreasing due to decrease in transfer function. 1000 Hz value has been chosen from linear zone to calculate $C_{\text{a-b}}$ which is LV side capacitance between the Phases A and B. For 1100 Hz, the data from FRA is as follows:

$$\left|\frac{V_{\text{out}}}{V_{\text{in}}}\right|_{\text{dB}} = -25\ \text{dB} \quad , \quad \angle\left(\frac{V_{\text{out}}}{V_{\text{in}}}\right)^{\circ} = \angle 95^{\circ}.$$

With the above values, Z_{Tr} is calculated by using Equations 3.9 and 3.10:

$$Z_{\text{Tr}} = -127.5 - j885.7\ \Omega.$$

From Z_{Tr}, the capacitance is calculated by using Equation 3.13 as

$$C_{\text{ab}} = 1.8 \cdot 10^{-7}\ F.$$

To find C_{bc}, 1000 Hz value has been chosen from linear zone of FRA of b-c. For 1000 Hz, the data from FRA of b-c is as follows:

$$\left|\frac{V_{\text{out}}}{V_{\text{in}}}\right|_{\text{dB}} = -16\ \text{dB} \quad , \quad \angle\left(\frac{V_{\text{out}}}{V_{\text{in}}}\right)^{\circ} = \angle 96^{\circ}.$$

With the above values, Z_{Tr} is calculated by using Equations 3.9 and 3.10:

$$Z_{\text{Tr}} = -82.97 - j313.75\ \Omega.$$

From Z_{Tr}, capacitance is calculated by using Equation 3.13 as

$$C_{\text{b-c}} = 5.07 \cdot 10^{-7}\ F.$$

FRA of b-c and FRA of c-a are the same. Therefore,

$$C_{\text{bc}} = C_{\text{ca}} = 5.07 \cdot 10^{-7}\ F.$$

3.6.3 Capacitive Coupling Calculations Between HV and LV Sides

As there is no FRA data between primary and secondary side, for the capacitive coupling between HV and LV sides, the parameters found for 415/15.75 kV have been taken for all phases. Therefore,

$$C_{\text{Aa}} = C_{\text{Bb}} = C_{\text{Cc}} = 8.95\ nF.$$

3.6.4 Stray Capacitance Calculations

As a similar approach in Section 3.4.4, the stray capacitance has been estimated for a appropriate division between the capacitances as

$$C_{\text{S}} = 2 \cdot 10^{-7}\ F.$$

This capacitance can be used for all phases. Therefore,

$$C_{\text{Sa}} = C_{\text{Sb}} = C_{\text{Sc}} = 2 \cdot 10^{-7}\ F.$$

After calculating each parameter, all of them can be shown in Table 3.7.

Table 3.7: Calculated parameters for 415/21.5 kV transformer.

Parameters	**Values**	**Parameters**	**Values**
L_{A}	27.96 H	C_{ab}	1.8 10^{-1} μF
L_{B}	38.7 H	C_{bc}	5.07 10^{-1} μF
L_{C}	31.45 H	C_{ca}	5.07 10^{-1} μF
L_{ab}	0.4633 H	C_{Aa}	8.95 nF
L_{bc}	0.257 H	C_{Bb}	8.95 nF
L_{ca}	0.257 H	C_{Cc}	8.95 nF
C_{A}	9.16 nF	C_{Sa}	$2 \cdot 10^{-1}$ μF
C_{B}	9.16 nF	C_{Sb}	$2 \cdot 10^{-1}$ μF
C_{C}	9.16 nF	C_{Sc}	$2 \cdot 10^{-1}$ μF

3.7 Modeling of 20/6.9 kV, 6.9/0.69 kV, and 690/400 V Transformers

In order to model 20/6.9 kV, 6.9/0.69 kV, and 690/400 V transformers of the second NPP, similar to the first NPP, the model offered by N.Sabiha has been used [2]. One phase of the used model and parameters can be found in Section 3.5.

3.8 Modeling of Surge Arresters

In this study, surge arresters have a considerable amount of importance as they are used to protect electrical equipment from over-voltage transients by mitigating the voltage level. For the first NPP, one surge arrester have been modeled in each phase of 400 kV, 15.75 kV, and 6 kV levels. For the second NPP, one surge arrester have been modeled in each phase of 400 kV, 20 kV, and 6.9 kV levels. Same surge arresters have been modeled for 15.75 kV and 20 kV levels as well as 6 kV and 6.9 kV levels. Although there are different models as IEEE Model, Fernandez, and Riaz Model, Pinceti Model has been used to model surge arresters for the simplicity of parameters [27], [28]. The model can be shown in Figure 3.11.

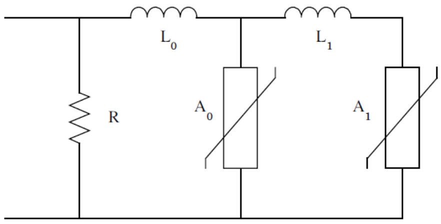

Figure 3.11: Pinceti model for surge arresters.

In this model, there are one parallel resistance of 1 $M\Omega$, 2 inductances as L_0 and L_1. A_0 and A_1 stand for surge arresters with non-linear characteristics. L_0 and L_1 (in μH) are defined as in Equations 3.14 and 3.15:

$$L_0 = \frac{1}{4} \cdot \frac{V_{r1/T_2} - V_{r8/20}}{V_{r8/20}} \cdot V_n \tag{3.14}$$

$$L_1 = \frac{1}{12} \cdot \frac{V_{r1/T_2} - V_{r8/20}}{V_{r8/20}} \cdot V_n \tag{3.15}$$

where

- V_n is the rated voltage of the surge arrester.
- V_{r1/T_2} is the residual voltage at 10 kA fast front current surge ($1/T_2$ μs).
- $V_{r8/20}$ is the residual voltage at 10 kA surge with a 8/20 μs shape.

However, the data for V_{r1/T_2} is not easy to find in the datasheets. Therefore, a modified formula for L_0 and L_1 (in mH) have been recommended by Pinceti [27]. L_0 and L_1 (in mH) can be expressed in Equations 3.16, 3.17 as

$$L_0 = 0.01 \cdot V_n \tag{3.16}$$

$$L_1 = 0.03 \cdot V_n. \tag{3.17}$$

The surge arresters have been chosen as Deepak Subedi's previous work [1]. The data of the selected surge arresters can be found in Table 3.8.

Table 3.8: Data of the selected surge arresters.

Voltage Level (kV)	**Current Class (kA)**	**Rated Voltage (kV)**	**Max COV (kV)**	**TOV for 1 sec (kV)**	**Max RV 8/20 μs 10 kA (kV)**	**Max RV 8/20 μs 20 kA (kV)**
6, 6.9	10	8.8	7	9.5	21.5	23.8
15.75, 20	10	24	19	27.4	58.4	73.8
400	20	336	269	394	808	881

By using Equation 3.16, Equation 3.17, and the data in Table 3.8, L_0 and L_1 for different voltage levels have been found as in Table 3.9.

Table 3.9: Calculated parameters for surge arresters.

Parameter	**Voltage Level**	**Values**
L_0	400 kV	0.00336 mH
L_1	400 kV	0.01008 mH
L_0	15.75 kV, 20 kV	0.00024 mH
L_1	15.75 kV, 20 kV	0.00072 mH
L_0	6 kV, 6.9 kV	0.00006 mH
L_1	6 kV, 6.9 kV	0.00018 mH

The data for A_0 and A_1 have been found by using V-I curve characteristics defined by IEEE. The characteristics of V-I curve are given in Appendix C. Before showing the characteristics of A_0 and A_1 for different voltage levels, the conversion from per-unit to actual voltages will be explained as the voltage values are given in per-unit. According to the conversion principle, the actual values for A_0 and A_1 are calculated by using Equation 3.18 [28]:

$$\text{Voltage (kV)} = \text{Voltage (pu)} \cdot \frac{V_{10}}{1.6} \tag{3.18}$$

where V_{10} is the residual voltage with 8/20 μs 10 kA discharge current.

According to Equation 3.18 and the data in Table 3.8, V-I curve parameters for A_0 and A_1 for different level surge arresters have been found as in Tables 3.10 and 3.11.

Table 3.10: Calculated V-I curve parameters of A_0 for different voltage levels.

I (kA)	**V (pu)**	**V (kV) for 400 kV Level**	**V (kV) for 15.75 kV and 20 kV Levels**	**V (kV) for 6 kV and 6.9 kV Levels**
0.01	1.4	707	51.1	18.8125
0.1	1.54	777.7	56.21	20.69375
1	1.68	848.4	61.32	22.575
2	1.74	878.7	63.51	23.38125
4	1.8	909	65.7	24.1875
6	1.82	919.1	66.43	24.45625
8	1.87	944.35	68.255	25.12813
10	1.9	959.5	69.35	25.53125
12	1.93	974.65	70.445	25.93438
14	1.97	994.85	71.905	26.47188
16	2	1010	73	26.875
18	2.05	1035.25	74.825	27.54688
20	2.1	1060.5	76.65	28.21875

Table 3.11: Calculated V-I curve parameters of A_1 for different voltage levels.

I (kA)	**V (pu)**	**V (kV) for 400 kV Level**	**V (kV) for 15.75 kV and 20 kV Levels**	**V (kV) for 6 kV and 6.9 kV levels**
0.1	1.23	621.15	44.895	16.52813
1	1.36	686.8	49.64	18.275
2	1.43	722.15	52.195	19.21563
4	1.48	747.4	54.02	19.8875
6	1.5	757.5	54.75	20.15625
8	1.53	772.65	55.845	20.55938
10	1.55	782.75	56.575	20.82813
12	1.56	787.8	56.94	20.9625
14	1.58	797.9	57.67	21.23125
16	1.59	802.95	58.035	21.36563
18	1.6	808	58.4	21.5
20	1.61	813.05	58.765	21.63438

The required parameters and data for Pinceti Model have been found above. Then, by using that data, the surge arresters for each level have been simulated with 8/20 μs 10 kA discharge current to ensure about their operation. The residual voltages according to these simulations can be found in the Figures 3.12, 3.13, 3.14.

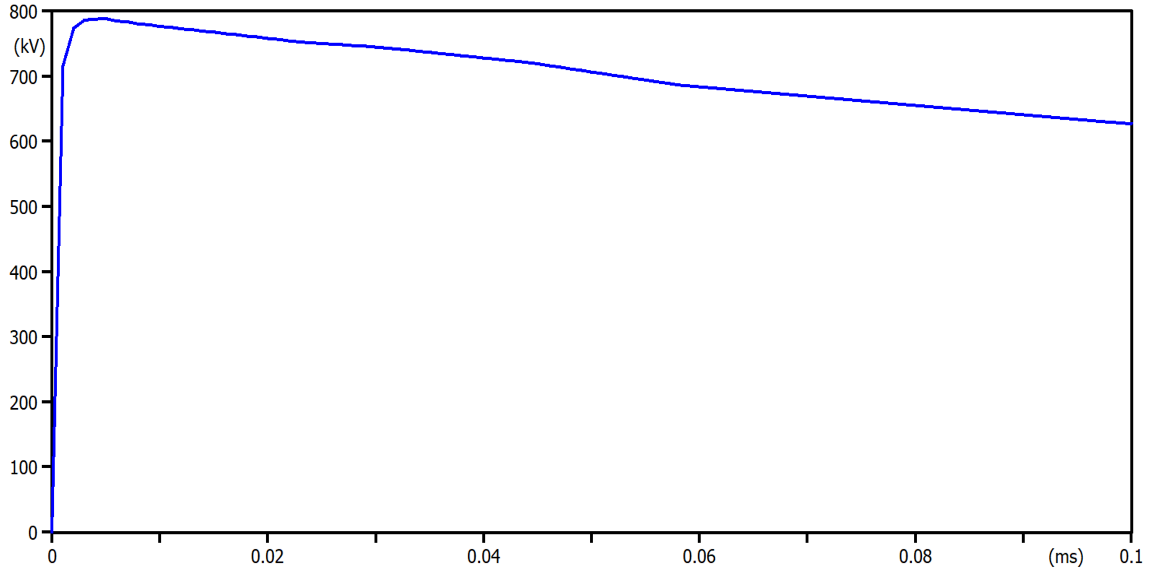

Figure 3.12: Residual voltage of the surge arrester in 400 kV level.

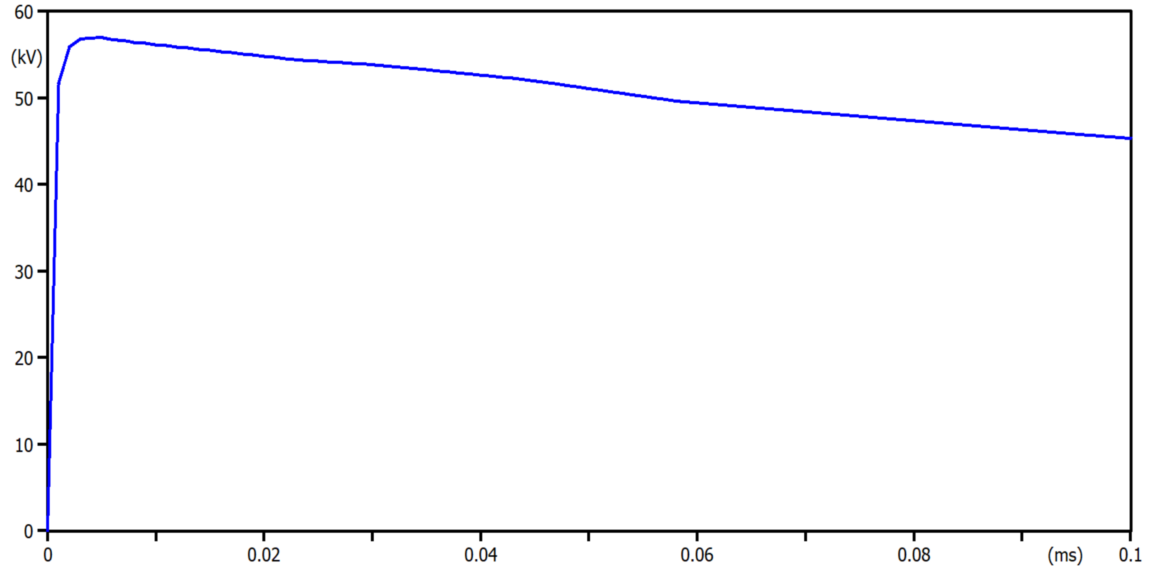

Figure 3.13: Residual voltage of the surge arrester in 15.75 kV and 20 kV levels.

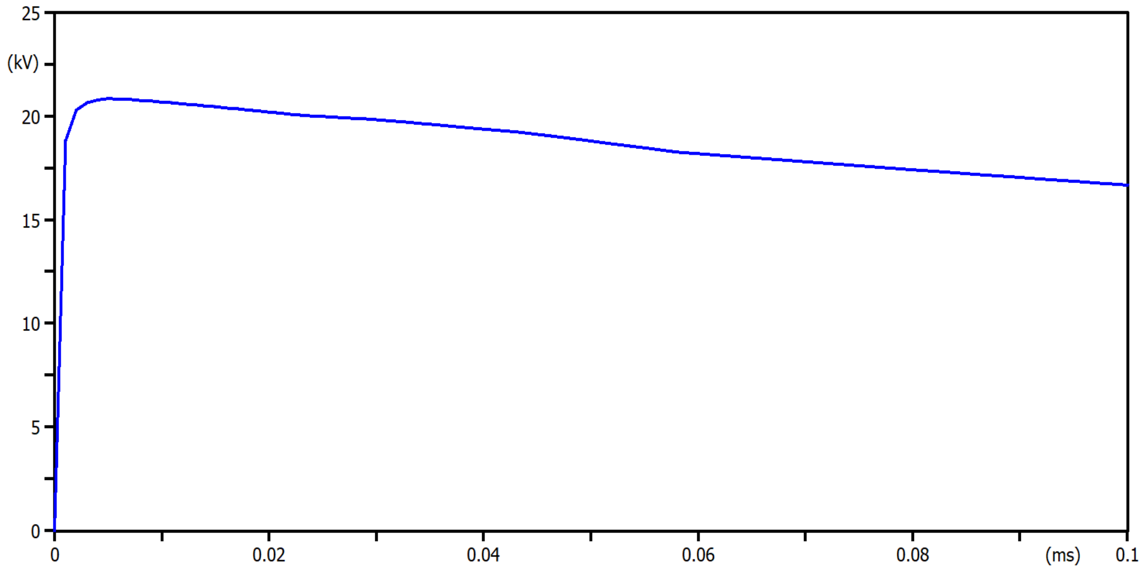

Figure 3.14: Residual voltage of the surge arrester in 6 kV and 6.9 kV levels.

According to the simulation results and datasheet values, the error for the residual voltages has been found as 2% for the surge arrester in 400 kV level, 0.8% for the surge arrester in 15.75 kV and 20 kV levels, and 0.1% for the surge arresters in 6 kV and 6.9 kV levels.

3.9 Overall Simulation Models

The overall simulation model for the first NPP including the lightning source, transmission towers, overhead lines, 415/15.75 kV, 15.75/6 kV, and 6/0.4 kV transformers, and surge arresters for 400 kV, 15.75 kV, and 6 kV levels will be shown in Figure 3.15.

The overall simulation model for the second NPP including the lightning source, transmission towers, overhead lines, 415/21.5 kV, 20/6.9 kV, 6.9/0.69 kV, and 690/400 V transformers, and surge arrester for 400 kV, 20 kV, and 6.9 kV levels will be shown in Figure 3.16.

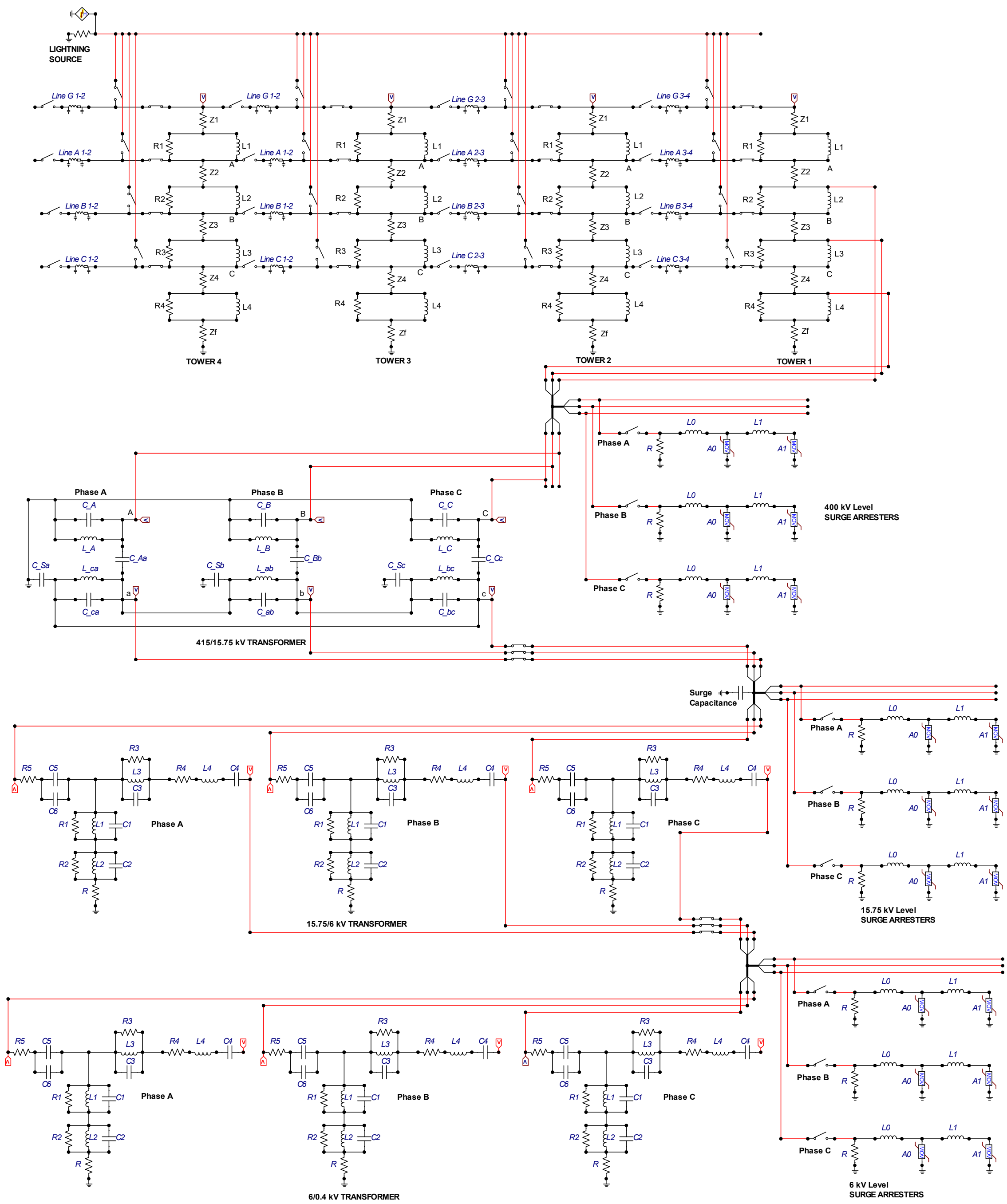

Figure 3.15: The overall simulation model for the first NPP.

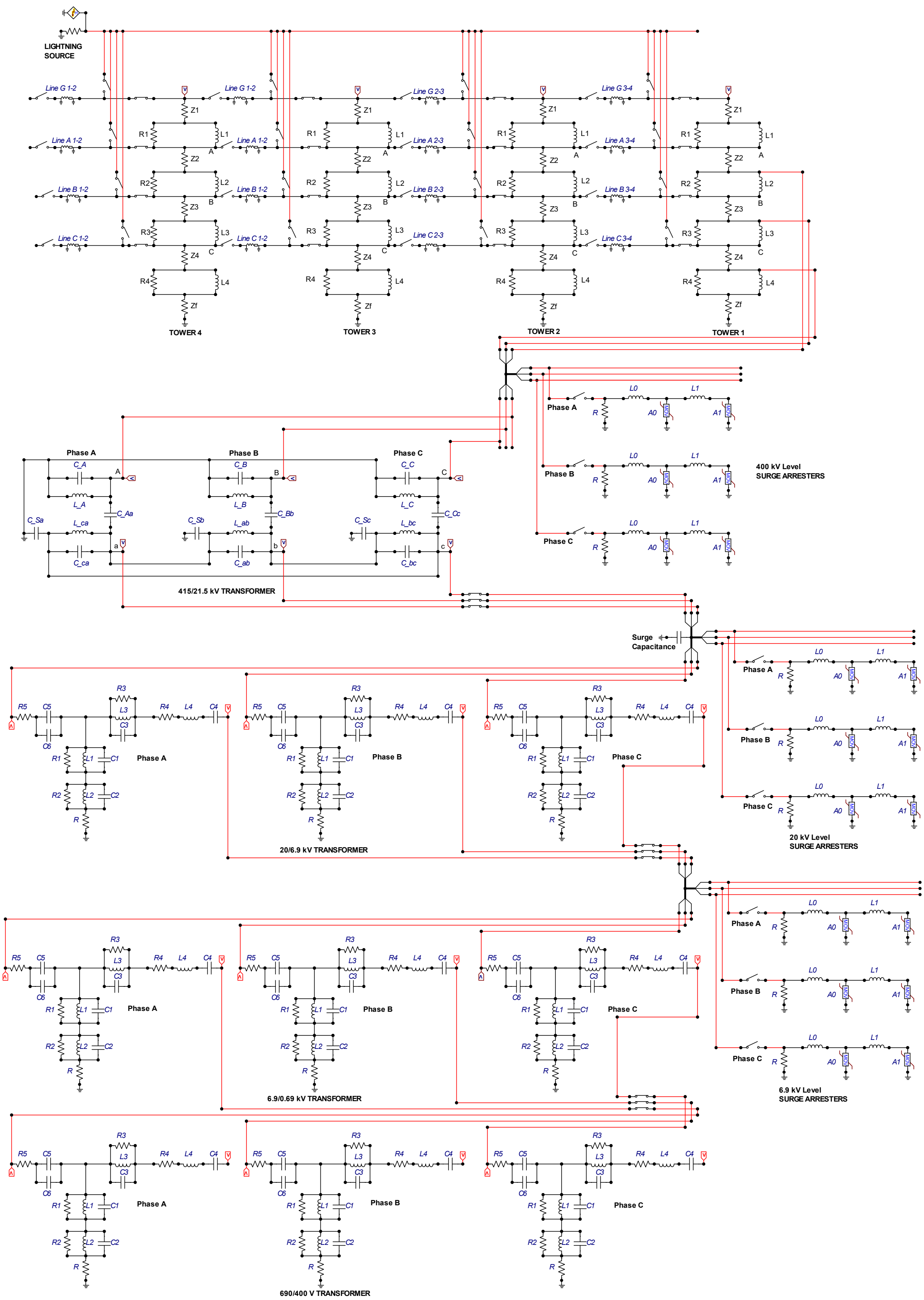

Figure 3.16: The overall simulation model for the second NPP.

4 Simulations and Results

4.1 Simulation Software

For the simulation of the overall models, ATPDraw software has been used. ATP is defined as Alternative Transient Program which is used widely to simulate the transient phenomenon that has electromagnetic characteristics. ATPDraw version enables users to model the circuit digitally with the mouse and by selecting the predefined components. In ATPDraw, standard components (R, L, C), nonlinear components, transformers, transmission line models, cable models, and lots of different special models exist [29]. In this study, models have been implemented into ATPDraw software, and simulations have been made.

4.2 Simulation Procedure

The models explained in the previous section were used to make different simulations. Simulations were made using 2 different parameters of the lightning source as 200 kA 1.2/50 μs and 20 kA 1.2/50 μs. The former one was used to investigate the results of direct stroke to the ground wire, and the latter one was used to investigate the results of direct stroke to the different phase conductors.

A variety of simulations were made by using different scenarios that were changed with the switches. In the simulations of the first NPP model, 4 towers, one surge arrester in each phase of 400 kV, 15.75 kV, and 6 kV levels, and one surge capacitance of 0.36 μF in 15.75 kV level have been used. In the simulations of the second NPP model, 4 towers, one surge arrester in each phase of 400 kV, 20 kV, and 6.9 kV levels, and one surge capacitance of 0.36 μF in 20 kV level have been used.

Firstly, the tower number has been adjusted to one and different combinations with the surge arresters have been investigated. Then, the tower number has been increased, and the similar procedure has been followed by also changing the tower exposed to the stroke. The measurements have been taken from the ground wire of the towers, and HV and LV sides of each transformer.

Simulations can be categorized into 4 main parts in terms of the lightning source parameters and the phase type exposed to the stroke as

1. 200 kA 1.2/50 μs Direct Stroke to the Ground Wire
2. 20 kA 1.2/50 μs Direct Stroke to the Phase A Conductor
3. 20 kA 1.2/50 μs Direct Stroke to the Phase B Conductor
4. 20 kA 1.2/50 μs Direct Stroke to the Phase C Conductor.

Each part has been simulated without a surge capacitance and with a surge capacitance respectively.

4.3 Simulation Results of the First NPP Model

In this part, the results of each simulation for the first NPP will be investigated in detail. To simplify, different combinations of surge arresters have been defined as "Cases". Also, "Scenarios" have been used for the different system models in terms of tower number and stroke location on the towers.

The cases could be assigned as follows:

- **Case 1**: None of the surge arresters are operating (Written as “None” in the figures).
- **Case 2**: One surge arrester in each phase of 400 kV level is operating (Written as “400 kV (All Phases)” in the figures).
- **Case 3**: One surge arrester in Phase A of 400 kV level is operating (Written as “400 kV (Phase A)” in the figures).
- **Case 4**: One surge arrester in each phase of 400 kV and 15.75 kV levels is operating (Written as “400 kV + 15.75 kV” in the figures).
- **Case 5**: One surge arrester in each phase of in 400 kV, 15.75 kV, and 6 kV levels is operating (Written as “400 kV + 15.75 kV + 6 kV” in the figures).
- **Case 6**: One surge arrester in Phase B of 400 kV level is operating (Written as “400 kV (Phase B)” in the figures).
- **Case 7**: One surge arrester in Phase C of 400 kV level is operating (Written as “400 kV (Phase C)” in the figures)

Simulation results will be given in 4 main parts in terms of the stroke type. In each main part, firstly, the simulation results without a surge capacitance will be given and discussions will be made on the results. Then, the results with a surge capacitance will be given, the discussion will be made, and results will be compared with the case without a surge capacitance.

In the first part, simulation graphs of Phase A, and transmission tower will be given for Case 1 and Case 2 with 1 existing tower scenario to demonstrate. The other results will be shown as figures.

In figures, it should be noted that the black color for the induced voltage values shows the safe values under BIL; whereas, the red color for the induced voltage values show the values above BIL. BILs for the equipment are given as

- 29 kV for 6 kV level
- 69 kV for 15.75 kV level
- 1640 kV for 400 kV level.

Also, it is worth to state that Tower 1 in the results is the rightmost tower which is closest to the primary transformer, and Tower 4 is the leftmost tower which is the furthest from the primary transformer.

4.3.1 Results for 200 kA 1.2/50 μs Direct Stroke to the Ground Wire Without a Surge Capacitance

In this part, the lightning source has been adjusted as 200 kA 1.2/50 μs and the ground wire of the tower was exposed to lightning stroke. No surge capacitance is used in the network. The simulation results in case of 1 existing tower for the Case 1 and Case 2 will be demonstrated in this part, and the results of the other cases will be given in Figure 4.11 on the next pages.

Case 1: None of the surge arresters are operating:

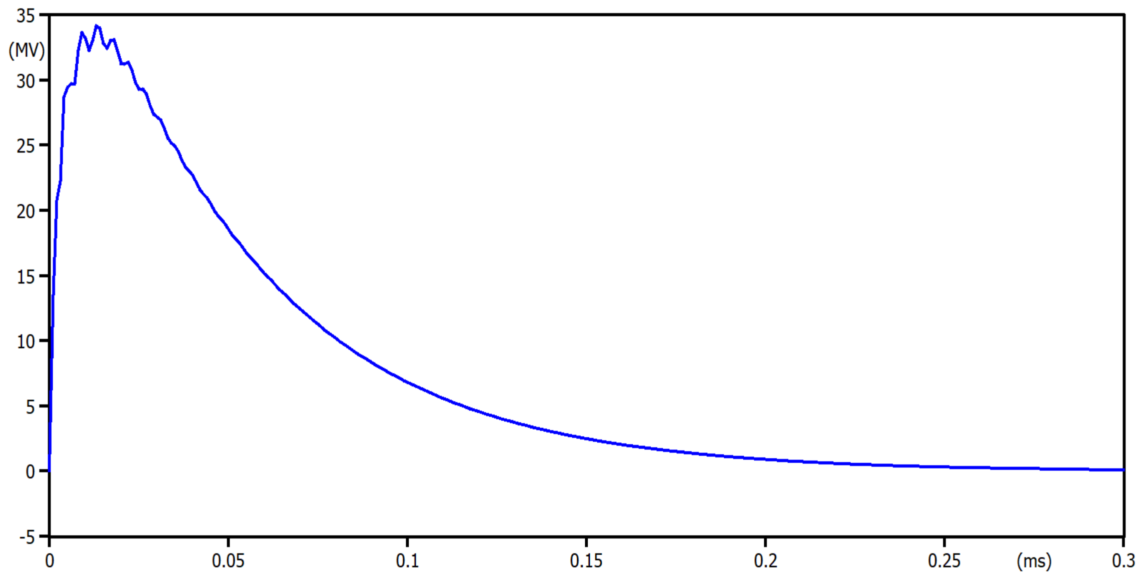

Figure 4.1: Induced voltage on the ground wire of tower 1 for case 1.

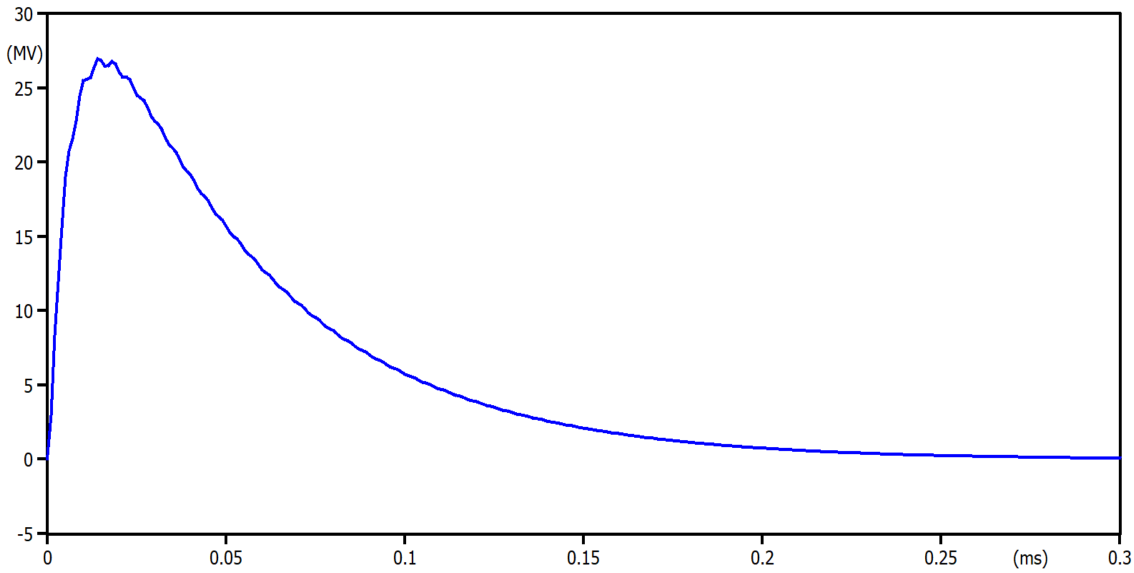

Figure 4.2: Induced voltage on 400 kV level for case 1.

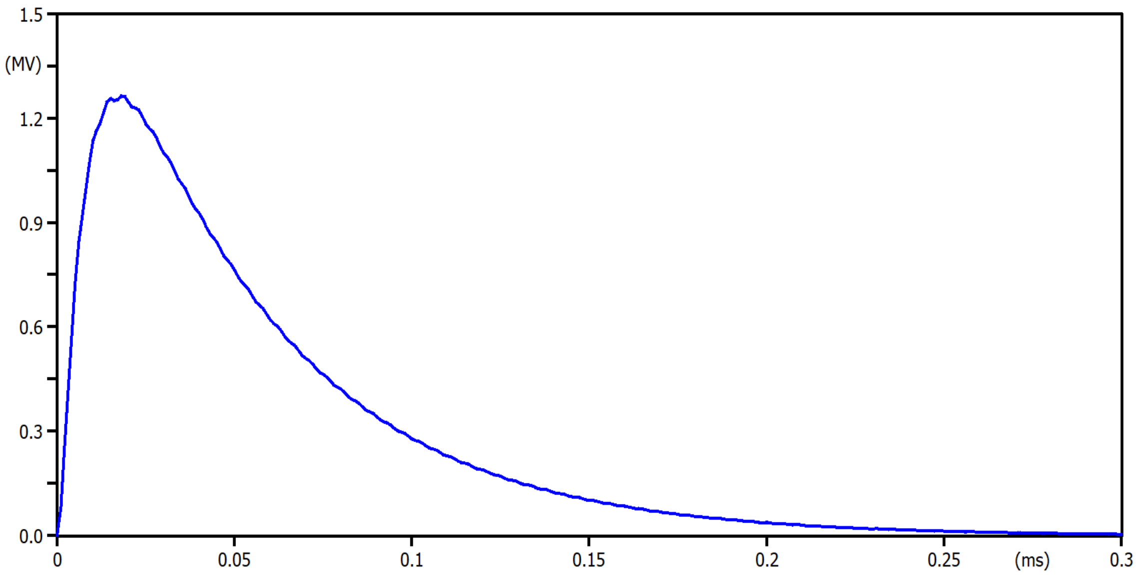

Figure 4.3: Induced voltage on 15.75 kV level for case 1.

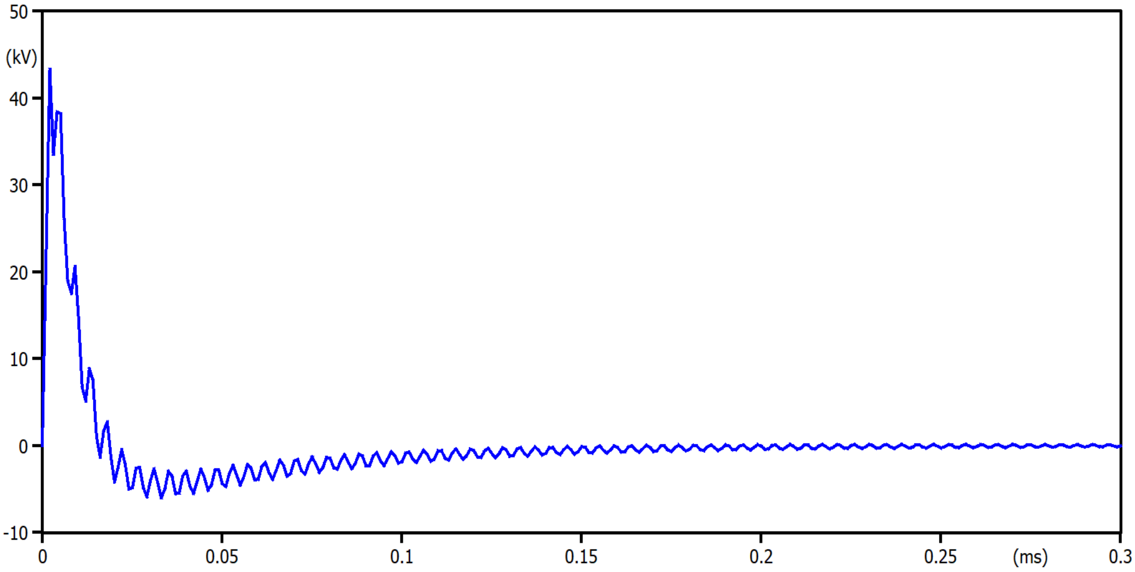

Figure 4.4: Induced voltage on 6 kV level for case 1.

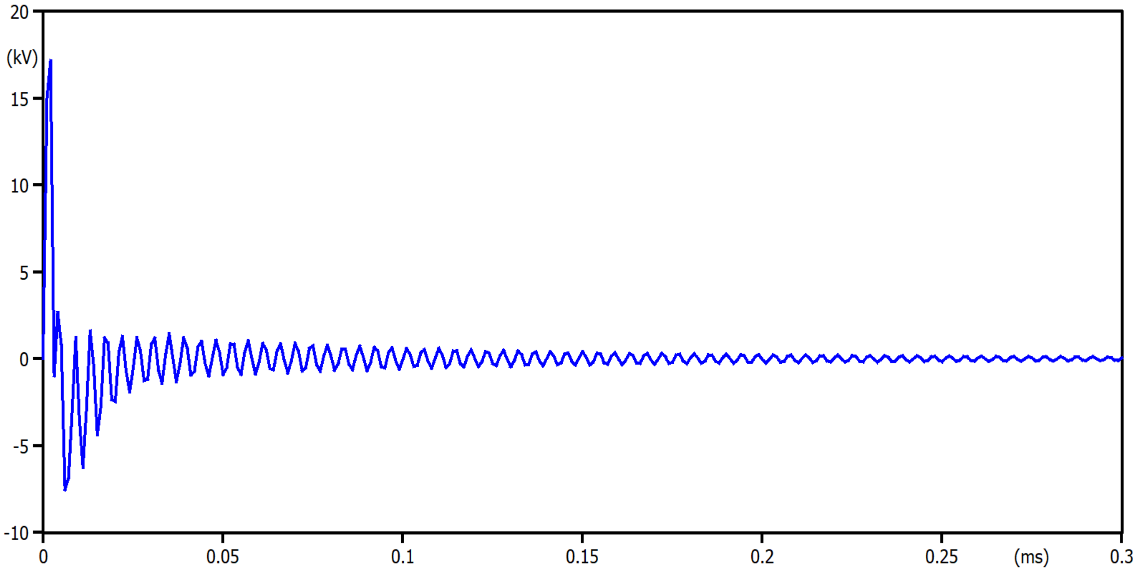

Figure 4.5: Induced voltage on 400 V level for case 1.

Case 2: One surge arrester in each phase of 400 kV level is operating:

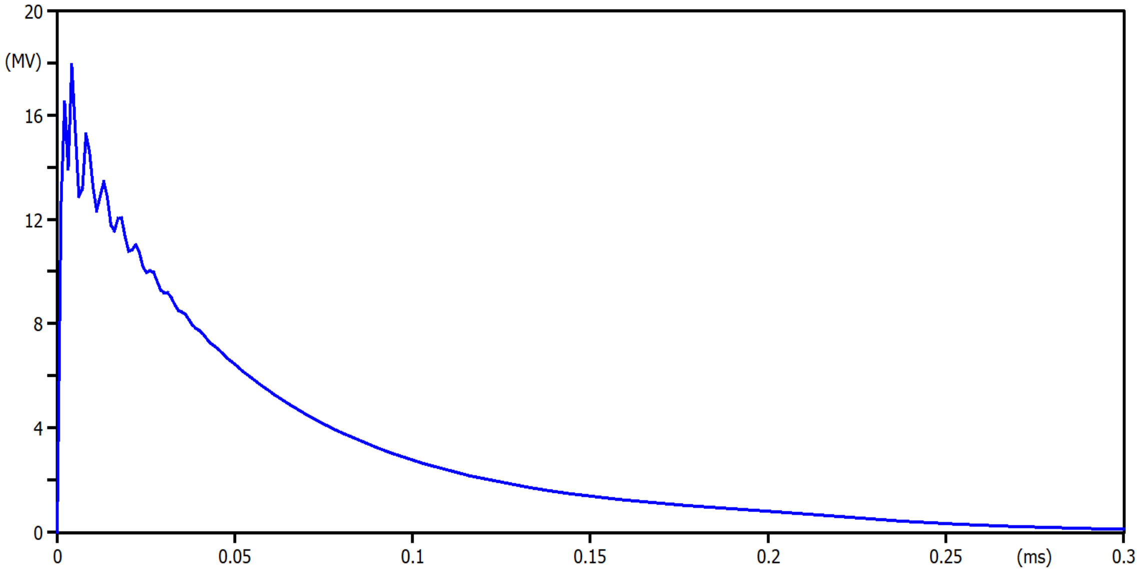

Figure 4.6: Induced voltage on the ground wire of tower 1 for case 2.

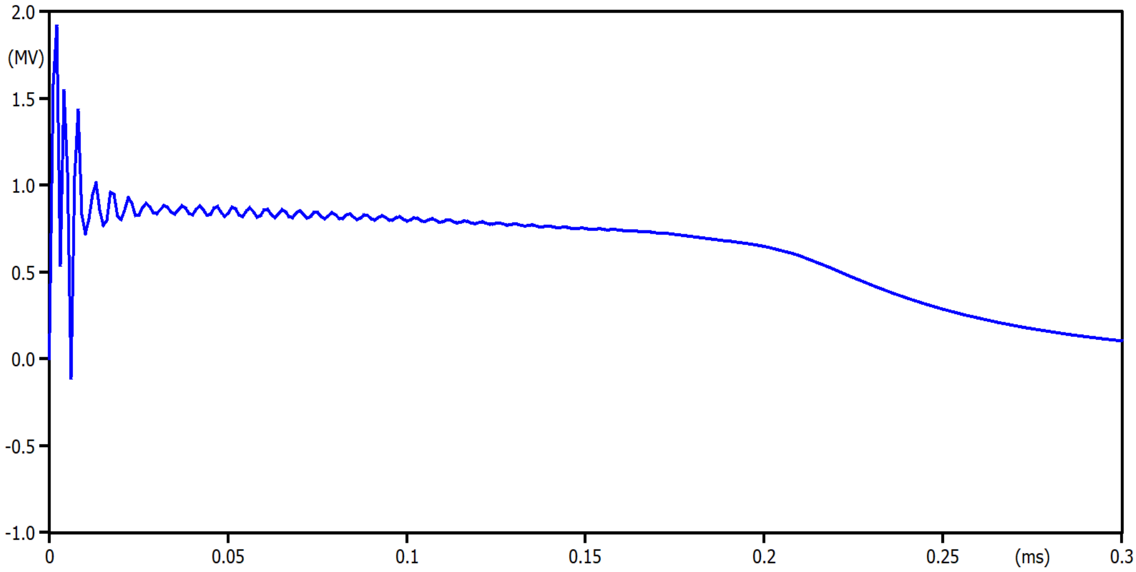

Figure 4.7: Induced voltage on 400 kV level for case 2.

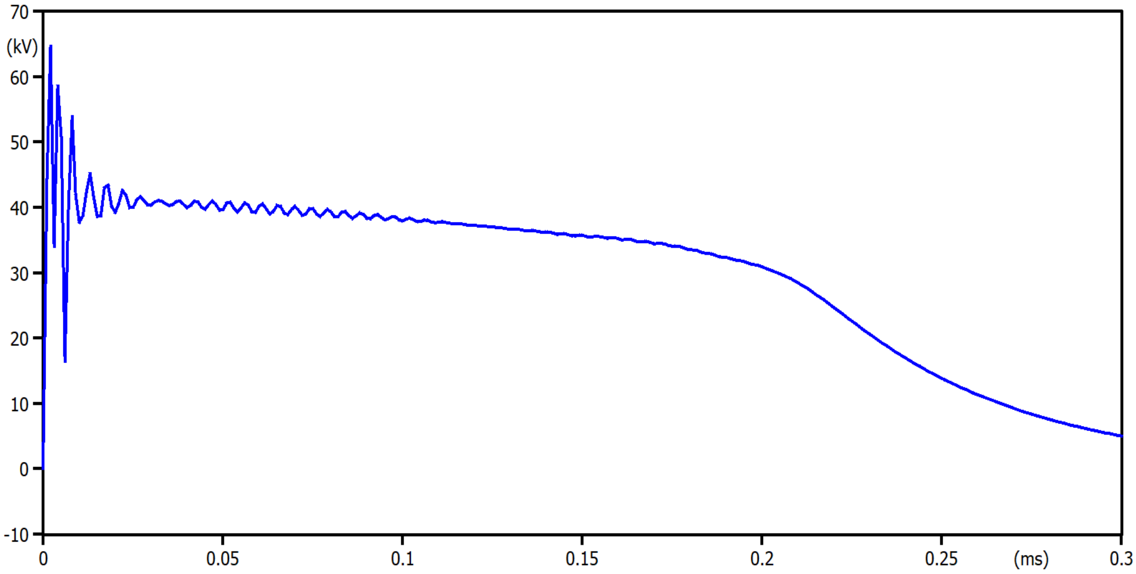

Figure 4.8: Induced voltage on 15.75 kV level for case 2.

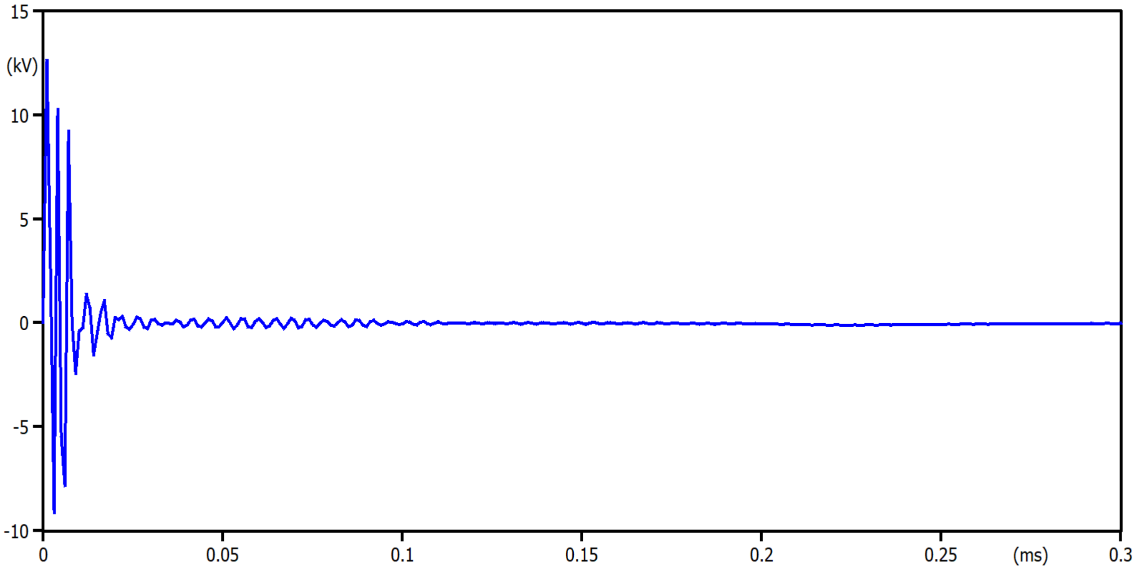

Figure 4.9: Induced voltage on 6 kV level for case 2.

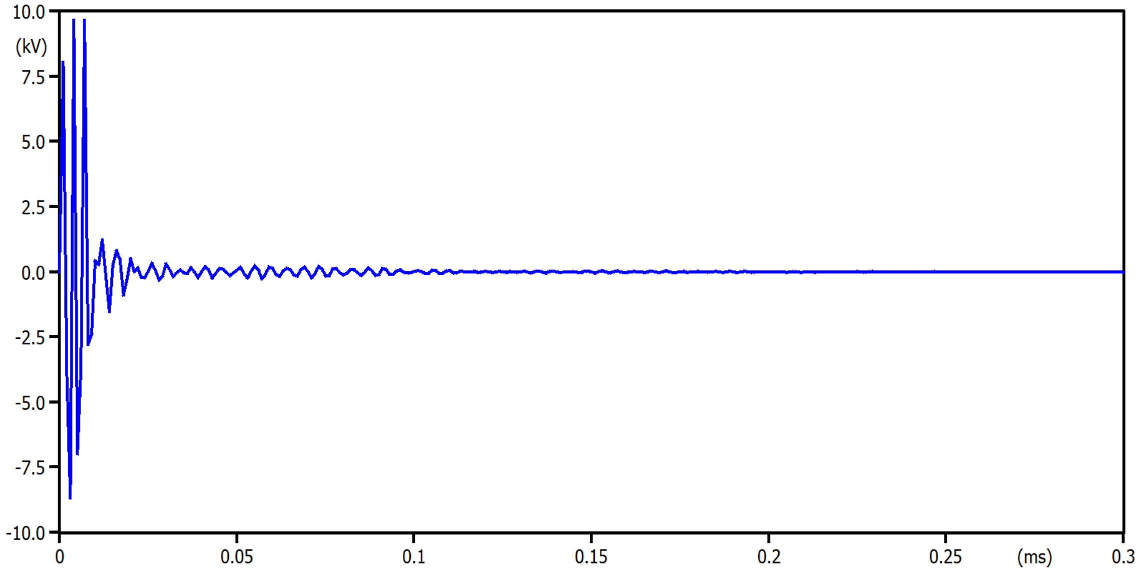

Figure 4.10: Induced voltage on 400 V level for case 2.

The results of all phases for the other cases and scenarios will be shown in Figure 4.11 on the next page.

For the results of different cases and scenarios in Figure 4.11, following discussions and comments can be made:

- For all scenarios, if the lightning strikes to the ground wire of the towers without operation of any surge arresters (Case 1), all phases of 400 kV, 15.75 kV, and 6 kV levels are above BIL.
- As the number of towers increases, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages in each level increases; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), Phase A of 400 kV level is above BIL if the stroke comes to the rightmost tower (Tower 1) or if there are 2 existing towers; whereas, the other phases of 400 kV level are below BIL. As the stroke hits to the left towers, the magnitude of the induced voltages in 400 kV level decreases making the magnitude of Phase A of 400 kV level below BIL except for 2 existing towers scenario.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage in all phases of 15.75 kV level is above BIL except for 1 existing tower scenario. Moreover, all phases of 6 kV level are below BIL for all scenarios.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 15.75 kV Side			Induced Voltage Peak on 6 kV Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	34 MV (T1)	27 MV	18.4 MV	10.2 MV	1.26 MV	1.35 MV	1.33 MV	43.3 kV	45 kV	44.4 kV	17.2 kV	18 kV	17.7 kV
		400 kV (All Phases)	18 MV (T1)	1.92 MV	758.3 kV	378.6 kV	64.6 kV	67.3 kV	66.4 kV	12.6 kV	12.9 kV	12.8 kV	9.7 kV	9.7 kV	9.6 kV
		400 kV (Phase A)	18 MV (T1)	1.92 MV	831.2 kV	405.6 kV	65.1 kV	67.9 kV	66.9 kV	12.6 kV	12.9 kV	12.8 kV	9.5 kV	9.5 kV	9.5 kV
		400 kV + 15.75 kV	18 MV (T1)	1.92 MV	757.5 kV	377.2 kV	55.2 kV	57.1 kV	56.2 kV	12.5 kV	12.8 kV	12.7 kV	11.1 kV	11.2 kV	11.1 kV
		400 kV + 15.75 kV + 6 kV	18 MV (T1)	1.92 MV	757.5 kV	377.2 kV	55.2 kV	57.1 kV	56.2 kV	12.4 kV	12.5 kV	12.5 kV	11.1 kV	11.2 kV	11.1 kV
2	1	None	24.3 MV (T1), 26 MV (T2)	20 MV	13.9 MV	7.7 MV	949.2 kV	1.01 MV	999.6 kV	38.8 kV	40.4 kV	39.9 kV	14.6 kV	15.4 kV	15.1 kV
		400 kV (All Phases)	14.4 MV (T1), 11.8 MV (T2)	1.81 MV	988.8 kV	782 kV	70.7 kV	75.6 kV	75.2 kV	12.5 kV	12.8 kV	12.7 kV	10.7 kV	10.7 kV	10.7 kV
		400 kV (Phase A)	14.4 MV (T1), 11.8 MV (T2)	1.81 MV	2.2 MV	1.41 MV	113.9 kV	124.4 kV	122.9 kV	14 kV	14.4 kV	14.3 kV	11.5 kV	11.6 kV	11.6 kV
		400 kV + 15.75 kV	14.4 MV (T1), 11.8 MV (T2)	1.81 MV	987.3 kV	780.6 kV	54.9 kV	57 kV	56.1 kV	12.5 kV	12.8 kV	12.7 kV	10.7 kV	10.7 kV	10.7 kV
		400 kV + 15.75 kV + 6 kV	14.4 MV (T1), 11.8 MV (T2)	1.81 MV	987.3 kV	780.6 kV	54.9 kV	57 kV	56.1 kV	12.4 kV	12.6 kV	12.5 kV	10.7 kV	10.7 kV	10.7 kV
	2	None	25.5 MV (T1), 27.5 MV (T2)	20.3 MV	13.8 MV	7.6 MV	952.7 kV	1.01 MV	1 MV	47 kV	49.9 kV	49.2 kV	16.8 kV	17.8 kV	17.6 kV
		400 kV (All Phases)	11.1 MV (T1), 18.7 MV (T2)	1.68 MV	1.14 MV	843.3 kV	80 kV	85.5 kV	84.7 kV	11.5 kV	12.2 kV	12.1 kV	4.8 kV	5.1 kV	5.1 kV
		400 kV (Phase A)	11.2 MV (T1), 18.7 MV (T2)	1.68 MV	2.77 MV	1.78 MV	137 kV	150.3 kV	148.4 kV	12.1 kV	12.9 kV	12.7 kV	5.5 kV	5.8 kV	5.7 kV
		400 kV + 15.75 kV	11.1 MV (T1), 18.7 MV (T2)	1.68 MV	1.14 MV	844.5 kV	55.9 kV	58.5 kV	57.7 kV	8.7 kV	9.1 kV	9 kV	4.3 kV	4.4 kV	4.4 kV
		400 kV + 15.75 kV + 6 kV	11.1 MV (T1), 18.7 MV (T2)	1.68 MV	1.14 MV	844.5 kV	55.9 kV	58.5 kV	57.7 kV	8.7 kV	9.1 kV	9 kV	4.3 kV	4.4 kV	4.4 kV
3	1	None	19.3 MV (T1), 19.3 MV (T2), 20.2 MV (T3)	15.7 MV	11.3 MV	6.3 MV	764.3 kV	815.5 kV	805.8 kV	38.3 kV	39.9 kV	39.4 kV	14.6 kV	15.1 kV	14.8 kV
		400 kV (All Phases)	14.3 MV (T1), 9.8 MV (T2), 9.7 MV (T3)	1.8 MV	938.6 kV	796.6 kV	69.2 kV	73.7 kV	73.4 kV	12.5 kV	12.8 kV	12.7 kV	10 kV	10 kV	9.9 kV
		400 kV (Phase A)	14.3 MV (T1), 9.9 MV (T2), 9.7 MV (T3)	1.8 MV	2.45 MV	1.68 MV	116 kV	128 kV	126.5 kV	12.5 kV	12.8 kV	12.7 kV	10.2 kV	10.3 kV	10.2 kV
		400 kV + 15.75 kV	14.3 MV (T1), 9.8 MV (T2), 9.7 MV (T3)	1.8 MV	938.8 kV	796.8 kV	54.7 kV	56.8 kV	55.9 kV	12.4 kV	12.7 kV	12.6 kV	11.3 kV	11.4 kV	11.4 kV
		400 kV + 15.75 kV + 6 kV	14.3 MV (T1), 9.8 MV (T2), 9.7 MV (T3)	1.8 MV	938.8 kV	796.8 kV	54.7 kV	56.8 kV	55.9 kV	12.4 kV	12.7 kV	12.6 kV	11.3 kV	11.4 kV	11.4 kV
	2	None	19.3 MV (T1), 19.3 MV (T2), 20.2 MV (T3)	15.5 MV	10.6 MV	5.9 MV	726.8 kV	774.8 kV	765.6 kV	37.7 kV	39.7 kV	39.1 kV	13 kV	13.8 kV	13.6 kV
		400 kV (All Phases)	9 MV (T1), 16.5 MV (T2), 13.6 MV (T3)	1.62 MV	1.09 MV	882.4 kV	74.5 kV	79.6 kV	78.9 kV	11 kV	11.7 kV	11.5 kV	4.5 kV	4.9 kV	4.8 kV
		400 kV (Phase A)	9.2 MV (T1), 16.5 MV (T2), 13.6 MV (T3)	1.62 MV	2.9 MV	1.99 MV	134.6 kV	148.8 kV	147 kV	11.4 kV	12.2 kV	12 kV	4.8 kV	5.2 kV	5.1 kV
		400 kV + 15.75 kV	9 MV (T1), 16.5 MV (T2), 13.6 MV (T3)	1.61 MV	1.09 MV	881.6 kV	54.7 kV	57.3 kV	56.5 kV	8.6 kV	9.1 kV	8.9 kV	4.6 kV	4.9 kV	4.7 kV
		400 kV + 15.75 kV + 6 kV	9 MV (T1), 16.5 MV (T2), 13.6 MV (T3)	1.61 MV	1.09 MV	881.6 kV	54.7 kV	57.3 kV	56.5 kV	8.6 kV	9.1 kV	8.9 kV	4.6 kV	4.9 kV	4.7 kV
	3	None	19.7 MV (T1), 20.2 MV (T2), 21 MV (T3)	16.6 MV	11.2 MV	6.1 MV	770.4 kV	820.1 kV	809.9 kV	46.4 kV	49.4 kV	48.7 kV	14.7 kV	15.7 kV	15.4 kV
		400 kV (All Phases)	8.5 MV (T1), 12.8 MV (T2), 19.1 MV (T3)	1.57 MV	1.13 MV	939 kV	79.8 kV	85.5 kV	85.2 kV	9.6 kV	10.3 kV	10.2 kV	4.3 kV	4.5 kV	4.4 kV
		400 kV (Phase A)	8.7 MV (T1), 12.8 MV (T2), 19.1 MV (T3)	1.59 MV	3.7 MV	2.55 MV	173.8 kV	192 kV	189.8 kV	11.7 kV	12.8 kV	12.6 kV	4.3 kV	4.5 kV	4.4 kV
		400 kV + 15.75 kV	8.5 MV (T1), 12.8 MV (T2), 19.1 MV (T3)	1.57 MV	1.13 MV	933.7 kV	58.2 kV	61.5 kV	60.7 kV	7.6 kV	8 kV	7.9 kV	4.3 kV	4.5 kV	4.4 kV
		400 kV + 15.75 kV + 6 kV	8.5 MV (T1), 12.8 MV (T2), 19.1 MV (T3)	1.57 MV	1.13 MV	933.7 kV	58.2 kV	61.5 kV	60.7 kV	7.6 kV	8 kV	7.9 kV	4.3 kV	4.5 kV	4.4 kV
4	1	None	18 MV (T1), 15.8 MV (T2), 17.4 MV (T3), 17.4 MV (T4)	13 MV	9.5 MV	5.4 MV	637.8 kV	680.9 kV	673 kV	38.3 kV	39.9 kV	39.3 kV	14.6 kV	15.1 kV	14.8 kV
		400 kV (All Phases)	14.3 MV (T1), 8.5 MV (T2), 8.5 MV (T3), 8.1 MV (T4)	1.8 MV	934.4 kV	773.3 kV	63.4 kV	66.3 kV	65.3 kV	12.5 kV	12.8 kV	12.7 kV	9.8 kV	9.8 kV	9.8 kV
		400 kV (Phase A)	14.3 MV (T1), 8.5 MV (T2), 8.5 MV (T3), 8.1 MV (T4)	1.8 MV	2.23 MV	1.54 MV	107.6 kV	118.5 kV	117.2 kV	12.5 kV	12.8 kV	12.7 kV	10 kV	10 kV	10 kV
		400 kV + 15.75 kV	14.3 MV (T1), 8.5 MV (T2), 8.5 MV (T3), 8.1 MV (T4)	1.8 MV	935 kV	773.3 kV	54.7 kV	56.8 kV	55.9 kV	12.4 kV	12.7 kV	12.6 kV	11.1 kV	11.2 kV	11.2 kV
		400 kV + 15.75 kV + 6 kV	14.3 MV (T1), 8.5 MV (T2), 8.5 MV (T3), 8.1 MV (T4)	1.8 MV	935 kV	773.3 kV	54.7 kV	56.8 kV	55.9 kV	12.4 kV	12.7 kV	12.6 kV	11.1 kV	11.2 kV	11.2 kV
	2	None	15.8 MV (T1), 16.6 MV (T2), 17.8 MV (T3), 16.2 MV (T4)	12.7 MV	8.9 MV	5 MV	606.6 kV	646.8 kV	639.3 kV	36.9 kV	38.8 kV	38.3 kV	12.5 kV	13.3 kV	13.1 kV
		400 kV (All Phases)	8.4 MV (T1), 16.4 MV (T2), 10.7 MV (T3), 11.5 MV (T4)	1.61 MV	1.08 MV	806.9 kV	73.7 kV	78.7 kV	78 kV	10.9 kV	11.6 kV	11.4 kV	4.5 kV	4.8 kV	4.8 kV
		400 kV (Phase A)	8.4 MV (T1), 16.4 MV (T2), 10.7 MV (T3), 11.5 MV (T4)	1.61 MV	2.52 MV	1.77 MV	120.1 kV	132.5 kV	131 kV	11.4 kV	12.1 kV	11.9 kV	4.8 kV	5.2 kV	5.1 kV
		400 kV + 15.75 kV	8.4 MV (T1), 16.4 MV (T2), 10.7 MV (T3), 11.5 MV (T4)	1.61 MV	1.07 MV	807.6 kV	54.7 kV	57.3 kV	56.4 kV	8.6 kV	9 kV	8.9 kV	4 kV	4.2 kV	4 kV
		400 kV + 15.75 kV + 6 kV	8.4 MV (T1), 16.4 MV (T2), 10.7 MV (T3), 11.5 MV (T4)	1.61 MV	1.07 MV	807.6 kV	54.7 kV	57.3 kV	56.4 kV	8.6 kV	9 kV	8.9 kV	4 kV	4.2 kV	4 kV
	3	None	17.6 MV (T1), 17.8 MV (T2), 16.9 MV (T3), 18.2 MV (T4)	14.7 MV	10.2 MV	5.6 MV	694.5 kV	740.4 kV	731.5 kV	34.1 kV	36.1 kV	35.7 kV	10.9 kV	11.6 kV	11.5 kV
		400 kV (All Phases)	7.7 MV (T1), 10.8 MV (T2), 16.8 MV (T3), 15.3 MV (T4)	1.5 MV	1.07 MV	924.5 kV	74.1 kV	79.5 kV	79.1 kV	9.1 kV	9.8 kV	9.7 kV	4.1 kV	4.3 kV	4.3 kV
		400 kV (Phase A)	7.9 MV (T1), 10.8 MV (T2), 16.8 MV (T3), 15.3 MV (T4)	1.52 MV	3.29 MV	2.28 MV	152.7 kV	168.9 kV	168 kV	10.7 kV	11.6 kV	11.5 kV	4.1 kV	4.3 kV	4.2 kV
		400 kV + 15.75 kV	7.7 MV (T1), 10.8 MV (T2), 16.8 MV (T3), 15.3 MV (T4)	1.5 MV	1.07 MV	923.8 kV	56.9 kV	60.1 kV	59.4 kV	7.2 kV	7.6 kV	7.5 kV	4.1 kV	4.3 kV	4.2 kV
		400 kV + 15.75 kV + 6 kV	7.7 MV (T1), 10.8 MV (T2), 16.8 MV (T3), 15.3 MV (T4)	1.5 MV	1.07 MV	923.8 kV	56.9 kV	60.1 kV	59.4 kV	7.2 kV	7.6 kV	7.5 kV	4.1 kV	4.3 kV	4.2 kV
	4	None	17 MV (T1), 16.1 MV (T2), 17.7 MV (T3), 19.1 MV (T4)	15.1 MV	10.7 MV	5.82 MV	724.3 kV	772.3 kV	762.9 kV	42.8 kV	45.6 kV	45 kV	12.6 kV	13.4 kV	13.2 kV
		400 kV (All Phases)	7.1 MV (T1), 10.5 MV (T2), 14.3 MV (T3), 19 MV (T4)	1.46 MV	1.08 MV	975 kV	77.1 kV	82.7 kV	82.5 kV	8.2 kV	8.7 kV	8.6 kV	4.1 kV	4.4 kV	4.1 kV
		400 kV (Phase A)	7.2 MV (T1), 10.6 MV (T2), 14.3 MV (T3), 19 MV (T4)	1.49 MV	3.98 MV	2.85 MV	185.4 kV	205.2 kV	203 kV	11 kV	12.1 kV	11.9 kV	4.1 kV	4.4 kV	4.3 kV
		400 kV + 15.75 kV	7.1 MV (T1), 10.5 MV (T2), 14.3 MV (T3), 19 MV (T4)	1.46 MV	1.08 MV	972.2 kV	58.6 kV	62.2 kV	61.6 kV	8.1 kV	8.6 kV	8.5 kV	4.1 kV	4.4 kV	4.3 kV
		400 kV + 15.75 kV + 6 kV	7.1 MV (T1), 10.5 MV (T2), 14.3 MV (T3), 19 MV (T4)	1.46 MV	1.08 MV	972.2 kV	58.6 kV	62.2 kV	61.6 kV	8.1 kV	8.6 kV	8.5 kV	4.1 kV	4.4 kV	4.3 kV

Figure 4.11: Results for 200 kA 1.2/50 μs direct stroke to the ground wire without a surge capacitance.

- When one surge arrester in Phase A of 400 kV level is operating (Case 3), although Phase A of 400 kV level stays almost constant, the induced voltage increases in the other phases of 400 kV level significantly compared to Case 2. Phase B and Phase C of 400 kV level values become more than BIL. Also, the induced voltage in all phases of 15.75 kV level increases significantly. There is a slight increase in 6 kV level; however, 6 kV level is below BIL for all scenarios .

- When one surge arrester in each phase of 400 kV and 15.75 kV levels is operating (Case 4), the magnitudes of induced voltages in 400 kV level are similar as the operation of only 400 kV level surge arresters (Case 2). On the other hand, induced voltage on 15.75 kV level decreases to safe region. Also, the induced voltages in 6 kV level also reduces slightly. Although there are some scenarios for which all the levels are below BIL, for most of the scenarios, the voltage level of Phase A of 400 kV level is above BIL.

- When one surge arrester in each phase of 400 kV, 15.75 kV, and 6 kV levels is operating (Case 5), all results are the same as protection with only 400 kV and 15.75 kV surge arresters (Case 4) except for 6 kV level. The magnitude of 6 kV level slightly reduces for some scenarios; however, for most of the scenarios this level stays constant. Hence, there is no need to operate 6 kV level surge arresters as they don't have significant effect.

- In this simulation, as can be seen from the results, when one surge arrester in each phase of 400 kV and 15.75 kV levels are operating (Case 4), all levels are below BIL except Phase A of 400 kV level. Phase A is above BIL for some scenarios. Although Case 4 is the safest case among the other cases, in order to make Phase A of 400 kV level below BIL, surge arrester with different ratings might be preferred.

4.3.2 Results for 200 kA 1.2/50 μs Direct Stroke to the Ground Wire With a Surge Capacitance

In this part, the lightning source has been adjusted as 200 kA 1.2/50 μs and the ground wire of the tower was exposed to lightning stroke. A surge capacitance of 0.36 μF is used in the network. The simulation results will be given in Figure 4.12 on the next page.

For the results of different cases and scenarios in Figure 4.12, following discussions and comments can be made:

- For all scenarios, the values in 400 kV level are almost the same as the case without a surge capacitance; whereas, the values in 15.75 kV and 6 kV level are significantly less than the case without a surge capacitance.

- For all scenarios, if lightning strikes to the ground wire of the towers without the operation of any surge arresters (Case 1), all phases of 400 kV and 15.75 kV levels are above BIL, and all phases of 6 kV level are below BIL.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 15.75 kV Side			Induced Voltage Peak on 6 kV Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	34 MV (T1)	26.8 MV	18.4 MV	10.2 MV	655.3 kV	741.5 kV	725.6 kV	22.2 kV	23.9 kV	23.6 kV	8.8 kV	9.7 kV	9.4 kV
		400 kV (All Phases)	18 MV (T1)	1.92 MV	758.7 kV	377.2 kV	33.4 kV	36.2 kV	35.3 kV	6.5 kV	6.8 kV	6.6 kV	4.9 kV	5 kV	4.9 kV
		400 kV (Phase A)	18 MV (T1)	1.92 MV	828.3 kV	402.6 kV	33.6 kV	36.5 kV	35.5 kV	6.5 kV	6.5 kV	6.6 kV	4.9 kV	5 kV	4.9 kV
		400 kV + 15.75 kV	18 MV (T1)	1.92 MV	758.7 kV	377.2 kV	33.4 kV	36.3 kV	35.3 kV	6.5 kV	6.8 kV	6.6 kV	4.9 kV	5 kV	4.9 kV
		400 kV + 15.75 kV + 6 kV	18 MV (T1)	1.92 MV	758.7 kV	377.2 kV	33.4 kV	36.2 kV	35.3 kV	6.5 kV	6.8 kV	6.6 kV	4.9 kV	5 kV	4.9 kV
2	1	None	24.3 MV (T1), 26 MV (T2)	20 MV	13.9 MV	7.7 MV	492.4 kV	557.7 kV	545.6 kV	19.9 kV	21.6 kV	21 kV	7.5 kV	8.3 kV	8.1 kV
		400 kV (All Phases)	14.4 MV (T1), 11.8 MV (T2)	1.81 MV	988.6 kV	781.2 kV	36.8 kV	41.9 kV	41.5 kV	6.4 kV	6.7 kV	6.6 kV	5.4 kV	5.5 kV	5.4 kV
		400 kV (Phase A)	14.4 MV (T1), 11.8 MV (T2)	1.81 MV	2.19 MV	1.41 MV	59.1 kV	69.9 kV	68.4 kV	7.1 kV	7.6 kV	7.5 kV	5.8 kV	6 kV	5.9 kV
		400 kV + 15.75 kV	14.4 MV (T1), 11.8 MV (T2)	1.81 MV	988.6 kV	781.2 kV	36.7 kV	41.8 kV	41.4 kV	6.4 kV	6.7 kV	6.6 kV	5.4 kV	5.5 kV	5.4 kV
		400 kV + 15.75 kV + 6 kV	14.4 MV (T1), 11.8 MV (T2)	1.81 MV	988.6 kV	781.2 kV	36.7 kV	41.8 kV	41.4 kV	6.4 kV	6.7 kV	6.6 kV	5.4 kV	5.5 kV	5.4 kV
	2	None	25.5 MV (T1), 27.5 MV (T2)	20.2 MV	13.7 MV	7.58 MV	493.3 kV	557.9 kV	545.8 kV	24.2 kV	27.2 kV	26.5 kV	8.6 kV	9.7 kV	9.4 kV
		400 kV (All Phases)	11.1 MV (T1), 18.7 MV (T2)	1.68 MV	1.14 MV	848.1 kV	41.7 kV	47.3 kV	45.6 kV	6 kV	6.7 kV	6.5 kV	2.5 kV	2.9 kV	2.8 kV
		400 kV (Phase A)	11.2 MV (T1), 18.7 MV (T2)	1.68 MV	2.77 MV	1.78 MV	71 kV	84.8 kV	82.8 kV	6.2 kV	7.1 kV	6.9 kV	2.8 kV	3.1 kV	3 kV
		400 kV + 15.75 kV	11.1 MV (T1), 18.7 MV (T2)	1.68 MV	1.14 MV	848.1 kV	41.4 kV	47 kV	46.2 kV	6 kV	6.7 kV	6.5 kV	2.5 kV	2.9 kV	2.8 kV
		400 kV + 15.75 kV + 6 kV	11.1 MV (T1), 18.7 MV (T2)	1.68 MV	1.14 MV	848.1 kV	41.4 kV	47 kV	46.2 kV	6 kV	6.7 kV	6.5 kV	2.5 kV	2.9 kV	2.8 kV
3	1	None	19.3 MV (T1), 19.3 MV (T2), 20.2 MV (T3)	15.7 MV	11.3 MV	6.3 MV	395.8 kV	449.2 kV	439.5 kV	19.7 kV	21.3 kV	20.8 kV	7.4 kV	8.2 kV	7.9 kV
		400 kV (All Phases)	14.3 MV (T1), 9.8 MV (T2), 9.7 MV (T3)	1.8 MV	938.6 kV	796.6 kV	38.9 kV	42.4 kV	40.4 kV	6.2 kV	7 kV	6.8 kV	5 kV	5 kV	5 kV
		400 kV (Phase A)	14.3 MV (T1), 9.9 MV (T2), 9.7 MV (T3)	1.8 MV	2.45 MV	1.68 MV	60.3 kV	72.7 kV	71.2 kV	6.4 kV	6.7 kV	6.6 kV	5.2 kV	5.2 kV	5.2 kV
		400 kV + 15.75 kV	14.3 MV (T1), 9.8 MV (T2), 9.7 MV (T3)	1.8 MV	938.8 kV	796.8 kV	38.6 kV	42 kV	40.1 kV	6.2 kV	7 kV	6.8 kV	5 kV	5 kV	5 kV
		400 kV + 15.75 kV + 6 kV	14.3 MV (T1), 9.8 MV (T2), 9.7 MV (T3)	1.8 MV	938.8 kV	796.8 kV	38.6 kV	42 kV	40.1 kV	6.2 kV	7 kV	6.8 kV	5 kV	5 kV	5 kV
	2	None	19.3 MV (T1), 19.3 MV (T2), 20.2 MV (T3)	15.3 MV	10.6 MV	5.9 MV	377.8 kV	428 kV	418.9 kV	19.3 kV	21.4 kV	20.9 kV	6.7 kV	7.5 kV	7.3 kV
		400 kV (All Phases)	9 MV (T1), 16.5 MV (T2), 13.6 MV (T3)	1.62 MV	1.09 MV	882.4 kV	38.8 kV	44.1 kV	43.4 kV	5.7 kV	6.4 kV	6.2 kV	2.4 kV	2.7 kV	2.6 kV
		400 kV (Phase A)	9.2 MV (T1), 16.5 MV (T2), 13.6 MV (T3)	1.62 MV	2.9 MV	1.99 MV	70 kV	84.6 kV	82.9 kV	5.9 kV	6.7 kV	6.5 kV	2.5 kV	2.9 kV	2.8 kV
		400 kV + 15.75 kV	9 MV (T1), 16.5 MV (T2), 13.6 MV (T3)	1.61 MV	1.09 MV	881.6 kV	38.7 kV	44 kV	43.3 kV	5.7 kV	6.4 kV	6.2 kV	2.4 kV	2.7 kV	2.6 kV
		400 kV + 15.75 kV + 6 kV	9 MV (T1), 16.5 MV (T2), 13.6 MV (T3)	1.61 MV	1.09 MV	881.6 kV	38.7 kV	44 kV	43.3 kV	5.7 kV	6.4 kV	6.2 kV	2.4 kV	2.7 kV	2.6 kV
	3	None	19.7 MV (T1), 20.2 MV (T2), 21 MV (T3)	16.6 MV	11.2 MV	6.1 MV	398.9 kV	450.8 kV	440.6 kV	23.9 kV	27 kV	26.3 kV	7.6 kV	8.5 kV	8.3 kV
		400 kV (All Phases)	8.5 MV (T1), 12.8 MV (T2), 19.1 MV (T3)	1.57 MV	1.13 MV	938 kV	41.6 kV	47.6 kV	47.2 kV	5 kV	5.8 kV	5.7 kV	2.2 kV	2.4 kV	2.4 kV
		400 kV (Phase A)	8.7 MV (T1), 12.8 MV (T2), 19.1 MV (T3)	1.59 MV	3.69 MV	2.55 MV	90.2 kV	108.9 kV	106.7 kV	6.1 kV	7.1 kV	6.9 kV	2.2 kV	2.5 kV	2.5 kV
		400 kV + 15.75 kV	8.5 MV (T1), 12.8 MV (T2), 19.1 MV (T3)	1.57 MV	1.13 MV	937.9 kV	41.2 kV	47.1 kV	46.7 kV	5 kV	5.8 kV	5.7 kV	2.2 kV	2.4 kV	2.4 kV
		400 kV + 15.75 kV + 6 kV	8.5 MV (T1), 12.8 MV (T2), 19.1 MV (T3)	1.57 MV	1.13 MV	937.9 kV	41.2 kV	47.1 kV	46.7 kV	5 kV	5.8 kV	5.7 kV	2.2 kV	2.4 kV	2.4 kV
4	1	None	18 MV (T1), 15.8 MV (T2), 17.4 MV (T3), 17.4 MV (T4)	13 MV	9.45 MV	5.4 MV	330.5 kV	375.4 kV	367.5 kV	19.6 kV	21.3 kV	20.7 kV	7.4 kV	8.2 kV	7.9 kV
		400 kV (All Phases)	14.3 MV (T1), 8.5 MV (T2), 8.5 MV (T3), 8.1 MV (T4)	1.8 MV	932.4 kV	774.3 kV	32.8 kV	36.4 kV	36 kV	6.4 kV	6.7 kV	6.6 kV	5 kV	4.9 kV	4.9 kV
		400 kV (Phase A)	14.3 MV (T1), 8.5 MV (T2), 8.5 MV (T3), 8.1 MV (T4)	1.8 MV	2.23 MV	1.53 MV	55.9 kV	67.2 kV	65.8 kV	6.4 kV	6.7 kV	6.6 kV	5.1 kV	5.1 kV	5.1 kV
		400 kV + 15.75 kV	14.3 MV (T1), 8.5 MV (T2), 8.5 MV (T3), 8.1 MV (T4)	1.8 MV	932.4 kV	774.3 kV	32.8 kV	36.4 kV	36 kV	6.4 kV	6.7 kV	6.6 kV	5 kV	5 kV	4.9 kV
		400 kV + 15.75 kV + 6 kV	14.3 MV (T1), 8.5 MV (T2), 8.5 MV (T3), 8.1 MV (T4)	1.8 MV	932.4 kV	774.3 kV	32.8 kV	36.4 kV	36 kV	6.4 kV	6.7 kV	6.6 kV	5 kV	5 kV	4.9 kV
	2	None	15.8 MV (T1), 16.6 MV (T2), 17.8 MV (T3), 16.2 MV (T4)	12.6 MV	8.86 MV	4.99 MV	315 kV	356.9 kV	349.4 kV	18.9 kV	20.9 kV	20.4 kV	6.5 kV	7.3 kV	7.1 kV
		400 kV (All Phases)	8.4 MV (T1), 16.4 MV (T2), 10.7 MV (T3), 11.5 MV (T4)	1.61 MV	1.08 MV	806.9 kV	35.6 kV	39.2 kV	38.7 kV	5.9 kV	6.6 kV	6.4 kV	2.5 kV	2.9 kV	2.8 kV
		400 kV (Phase A)	8.4 MV (T1), 16.4 MV (T2), 10.7 MV (T3), 11.5 MV (T4)	1.61 MV	2.52 MV	1.76 MV	62.4 kV	75.2 kV	73.7 kV	5.9 kV	6.6 kV	6.4 kV	2.5 kV	2.9 kV	2.8 kV
		400 kV + 15.75 kV	8.4 MV (T1), 16.4 MV (T2), 10.7 MV (T3), 11.5 MV (T4)	1.61 MV	1.07 MV	807.6 kV	35.6 kV	39.2 kV	38.7 kV	5.9 kV	6.6 kV	6.4 kV	2.5 kV	2.9 kV	2.8 kV
		400 kV + 15.75 kV + 6 kV	8.4 MV (T1), 16.4 MV (T2), 10.7 MV (T3), 11.5 MV (T4)	1.61 MV	1.07 MV	807.6 kV	35.6 kV	39.2 kV	38.7 kV	5.9 kV	6.6 kV	6.4 kV	2.5 kV	2.9 kV	2.8 kV
	3	None	17.6 MV (T1), 17.8 MV (T2), 16.9 MV (T3), 18.2 MV (T4)	14.7 MV	10.2 MV	5.6 MV	360.8 kV	408.7 kV	399.8 kV	17.5 kV	19.6 kV	19.1 kV	5.6 kV	6.3 kV	6.2 kV
		400 kV (All Phases)	7.7 MV (T1), 10.8 MV (T2), 16.8 MV (T3), 15.3 MV (T4)	1.5 MV	1.07 MV	926.2 kV	37.9 kV	44.3 kV	43.9 kV	4.7 kV	5.5 kV	5.4 kV	2.1 kV	2.3 kV	2.3 kV
		400 kV (Phase A)	7.9 MV (T1), 10.8 MV (T2), 16.8 MV (T3), 15.3 MV (T4)	1.52 MV	3.29 MV	2.28 MV	79.5 kV	96.1 kV	94.2 kV	5.5 kV	6.5 kV	6.3 kV	2.1 kV	2.3 kV	2.3 kV
		400 kV + 15.75 kV	7.7 MV (T1), 10.8 MV (T2), 16.8 MV (T3), 15.3 MV (T4)	1.5 MV	1.08 MV	926.1 kV	38.5 kV	44.1 kV	43.7 kV	4.7 kV	5.5 kV	5.4 kV	2.1 kV	2.3 kV	2.3 kV
		400 kV + 15.75 kV + 6 kV	7.7 MV (T1), 10.8 MV (T2), 16.8 MV (T3), 15.3 MV (T4)	1.5 MV	1.08 MV	926.1 kV	38.5 kV	44.1 kV	43.7 kV	4.7 kV	5.5 kV	5.4 kV	2.1 kV	2.3 kV	2.3 kV
	4	None	17 MV (T1), 16.1 MV (T2), 17.7 MV (T3), 19.1 MV (T4)	15.1 MV	10.7 MV	5.8 MV	375.3 kV	425.4 kV	416 kV	22 kV	24.9 kV	24.4 kV	6.5 kV	7.3 kV	7.2 kV
		400 kV (All Phases)	7.1 MV (T1), 10.5 MV (T2), 14.3 MV (T3), 19 MV (T4)	1.46 MV	1.08 MV	977.2 kV	40.2 kV	46.1 kV	45.8 kV	4.2 kV	4.8 kV	4.7 kV	2.1 kV	2.4 kV	2.4 kV
		400 kV (Phase A)	7.2 MV (T1), 10.6 MV (T2), 14.3 MV (T3), 19 MV (T4)	1.49 MV	3.98 MV	2.84 MV	96.2 kV	116.5 kV	114.3 kV	5.7 kV	6.8 kV	6.6 kV	2.1 kV	2.4 kV	2.4 kV
		400 kV + 15.75 kV	7.1 MV (T1), 10.5 MV (T2), 14.3 MV (T3), 19 MV (T4)	1.46 MV	1.08 MV	977.1 kV	39.9 kV	45.7 kV	45.5 kV	4.2 kV	4.7 kV	4.7 kV	2.1 kV	2.4 kV	2.4 kV
		400 kV + 15.75 kV + 6 kV	7.1 MV (T1), 10.5 MV (T2), 14.3 MV (T3), 19 MV (T4)	1.46 MV	1.08 MV	977.1 kV	39.9 kV	45.7 kV	45.5 kV	4.2 kV	4.7 kV	4.7 kV	2.1 kV	2.4 kV	2.4 kV

Figure 4.12: Results for 200 kA 1.2/50 μs direct stroke to the ground wire with a surge capacitance.

- As the number of towers increases, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), Phase A of 400 kV level is above BIL if the stroke comes to the rightmost tower or if there are 2 existing towers; whereas, the other levels are below BIL. As the stroke hits to the left towers, the magnitude of the induced voltages in 400 kV level decreases making the magnitude of Phase A of 400 kV level below BIL except for 2 existing towers scenario.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage in all phases of 15.75 kV level is below BIL.
- When one surge arrester in Phase A of 400 kV level is operating (Case 3), although Phase A of 400 kV level stays almost constant, the induced voltage increases in the other phases and levels. Phase B and Phase C of 400 kV level for all scenarios, and 15.75 kV for most of the scenarios become more than BIL. For 6 kV level, although there is an increase in the magnitudes slightly, the magnitudes of the induced voltages in all phases are below BIL.
- When one surge arrester in each phase of 400 kV and 15.75 kV levels is operating (Case 4), the magnitudes of induced voltages in 400 kV level are similar as the operation of one surge arrester in each phase of 400 kV level (Case 2). Although there are some scenarios for which all the levels are below BIL, for most of the scenarios, the voltage level in Phase A of 400 kV level is above BIL. Also, for 15.75 kV level, there is no significant effect of the operation of the surge arresters. As 15.75 kV level is already below BIL without the operation of the surge arresters in that level, there is no need to operate surge arresters in 15.75 kV level.
- When one surge arrester in each phase of 400 kV, 15.75 kV, and 6 kV levels is operating (Case 5), all results are almost the same as Case 2 and Case 4. There is no significant effect of operating the surge arresters in 6 kV level.
- In this simulation, as can be seen from the results, when one surge arrester in each phase of 400 kV is operating (Case 2), all levels are below BIL except Phase A of 400 kV level. Phase A is above BIL for some scenarios. Also, results showed that surge capacitance usage in 15.75 kV level makes the operation of surge arresters in 15.75 kV level unnecessary. Although Case 2 is the safest case among the other cases, in order to make Phase A of 400 kV level below BIL, surge arrester with different ratings might be preferred.

4.3.3 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase A Conductor Without a Surge Capacitance

In this part, the lightning source has been adjusted as 20 kA 1.2/50 μs and the Phase A conductor of the tower was exposed to lightning stroke. No surge capacitance is used in the network. The results are demonstrated in Figure 4.13 on the next page.

For the results of different cases and scenarios in Figure 4.13, following discussions and comments can be made:

– When the lightning strikes to Phase A conductor of the towers without the operation of any surge arresters (Case 1), in case of 1 existing tower, Phase A and Phase B of 400 kV level are above BIL. In case of 2 and 3 existing towers, Phase A of 400 kV level is above BIL. In case of 4 existing towers, all phases of 400 kV level are below BIL.

– When the lightning strikes to Phase A conductor of the towers without any protection (Case 1), in case of 1, 2, and 3 existing towers, all phases of 15.75 kV level are above BIL. In case of 4 existing towers, if the lightning strikes to the third or fourth tower, all phases of 15.75 kV level are above BIL. If the lightning strikes to the second tower, all phases of 15.75 kV level are below BIL. If the lightning strikes to the first tower, Phase A of 15.75 kV level is below BIL; whereas, Phase B and Phase C of 15.75 kV levels are above BIL. Moreover, all phases of 6 kV level are below BIL for all scenarios.

– As the number of towers increase, the magnitude of the induced voltages on each level decreases.

– As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.

– When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage magnitude on each level is below BIL.

– When one surge arrester in Phase A of 400 kV level is operating (Case 3), the results are slightly more than the results in Case 2. Induced voltage on each level is below BIL.

– When one surge arrester in each phase of 400 kV and 15.75 kV levels is operating (Case 4), the results are similar as Case 2 and Case 3. Operation of the surge arresters in 15.75 kV level does not have significant effect. Therefore, this case hasn't been simulated for the next studies.

– When one surge arrester in each phase of 400 kV, 15.75 kV, and 6 kV levels is operating (Case 5), the results are almost the same as Case 2 and Case 4. Operation of the surge arresters in 6 kV level does not have significant effect. Therefore, this case hasn't been simulated for the next studies.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 15.75 kV Side			Induced Voltage Peak on 6 kV Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	3.05 MV (T1)	3.05 MV	2.08 MV	1.15 MV	142.8 kV	152.2 kV	150.3 kV	5.5 kV	5.7 kV	5.6 kV	2.4 kV	2.4 kV	2.4 kV
		400 kV (All Phases)	914.4 kV (T1)	946 kV	563.2 kV	305.7 kV	38.9 kV	41.3 kV	40.8 kV	3.9 kV	4.1 kV	4 kV	2.4 kV	2.4 kV	2.4 kV
		400 kV (Phase A)	914.4 kV (T1)	946 kV	563.7 kV	306 kV	38.9 kV	41.3 kV	40.8 kV	3.9 kV	4.1 kV	4 kV	2.4 kV	2.4 kV	2.4 kV
		400 kV + 15.75 kV	914.4 kV (T1)	946 kV	563.1 kV	305.7 kV	38.8 kV	41.2 kV	40.7 kV	3.9 kV	4.1 kV	4 kV	2.4 kV	2.4 kV	2.4 kV
		400 kV + 15.75 kV + 6 kV	914.4 kV (T1)	946 kV	563.1 kV	305.7 kV	38.8 kV	41.2 kV	40.7 kV	3.9 kV	4.1 kV	4 kV	2.4 kV	2.4 kV	2.4 kV
2	1	None	2.16 MV (T1), 2.2 MV (T2)	2.12 MV	1.48 MV	823.2 kV	101.3 kV	108 kV	106.7 kV	5.1 kV	5.3 kV	5.2 kV	2.3 kV	2.4 kV	2.3 kV
		400 kV (All Phases)	939.5 kV (T1), 1 MV (T2)	921.6 kV	611.5 kV	359.6 kV	40 kV	42.7 kV	42.2 kV	3.7 kV	3.7 kV	3.7 kV	2.3 kV	2.4 kV	2.3 kV
		400 kV (Phase A)	939.6 kV (T1), 1.03 MV (T2)	921.6 kV	613.3 kV	360.6 kV	41 kV	42.8 kV	42.3 kV	3.7 kV	3.7 kV	3.7 kV	2.3 kV	2.4 kV	2.3 kV
		400 kV + 15.75 kV	939.5 kV (T1), 1.03 MV (T2)	921.6 kV	611.4 kV	359.5 kV	39.9 kV	42.5 kV	42 kV	3.7 kV	3.7 kV	3.7 kV	2.3 kV	2.4 kV	2.3 kV
		400 kV + 15.75 kV + 6 kV	834.5 kV (T1), 993.3 kV (T2)	867.6 kV	582.1 kV	342 kV	39 kV	41.6 kV	41.2 kV	3.7 kV	3.7 kV	3.7 kV	2.3 kV	2.4 kV	2.3 kV
	2	None	2.19 MV (T1), 2.38 MV (T2)	2.2 MV	1.49 MV	812.9 kV	102.7 kV	109.3 kV	108 kV	5.1 kV	5.4 kV	5.4 kV	1.8 kV	1.9 kV	1.9 kV
		400 kV (All Phases)	1.22 MV (T1), 1.11 MV (T2)	945.2 kV	729.5 kV	417.8 kV	44.2 kV	47.6 kV	46.9 kV	4.5 kV	4.5 kV	4.5 kV	1.6 kV	1.6 kV	1.6 kV
		400 kV (Phase A)	1.22 MV (T1), 1.11 MV (T2)	945.7 kV	768.6 kV	440.3 kV	45.4 kV	48.9 kV	48.2 kV	4.5 kV	4.5 kV	4.5 kV	1.3 kV	1.4 kV	1.3 kV
3	1	None	1.66 MV (T1), 1.62 MV (T2), 1.76 MV (T3)	1.7 MV	1.17 MV	665.6 kV	80.8 kV	86 kV	85 kV	5.1 kV	5.3 kV	5.2 kV	2.3 kV	2.4 kV	2.3 kV
		400 kV (All Phases)	866.7 kV (T1), 996.2 kV (T2), 1.04 MV (T3)	920.4 kV	596.9 kV	352 kV	39.8 kV	42.5 kV	42 kV	3.7 kV	3.9 kV	3.8 kV	2.3 kV	2.4 kV	2.3 kV
		400 kV (Phase A)	866.8 kV (T1), 996.2 kV (T2), 1.04 kV (T3)	920.4 kV	598.2 kV	352.3 kV	39.8 kV	42.6 kV	42.1 kV	3.7 kV	3.9 kV	3.8 kV	2.3 kV	2.4 kV	2.3 kV
	2	None	1.63 MV (T1), 1.75 MV (T2), 1.77 MV (T3)	1.64 MV	1.12 MV	624.4 kV	77.1 kV	82.1 kV	81.2 kV	4.1 kV	4.3 kV	4.2 kV	1.4 kV	1.5 kV	1.4 kV
		400 kV (All Phases)	1.04 MV (T1), 1.26 MV (T2), 1.1 MV (T3)	868.5 kV	687.7 kV	414.4 kV	44.1 kV	47.2 kV	46.7 kV	3.9 kV	4.2 kV	4.1 kV	1.3 kV	1.4 kV	1.4 kV
		400 kV (Phase A)	1.04 MV (T1), 1.26 MV (T2), 1.1 MV (T3)	868.5 kV	725 kV	425.5 kV	45.1 kV	48.5 kV	47.9 kV	3.9 kV	4.2 kV	4.1 kV	1.3 kV	1.4 kV	1.4 kV
	3	None	1.69 MV (T1), 1.7 MV (T2), 1.85 MV (T3)	1.67 MV	1.2 MV	650.8 kV	79.8 kV	85.2 kV	84.1 kV	4.8 kV	5.1 kV	5 kV	1.5 kV	1.6 kV	1.6 kV
		400 kV (All Phases)	1.25 MV (T1), 1.08 MV (T2), 1.15 MV (T3)	911.9 kV	757.4 kV	471 kV	46.4 kV	49.9 kV	49.3 kV	4.2 kV	4.4 kV	4.4 kV	1.4 kV	1.5 kV	1.5 kV
		400 kV (Phase A)	1.25 MV (T1), 1.08 MV (T2), 1.15 MV (T3)	912.6 kV	814.7 kV	504kV	48 kV	51.8 kV	51.1 kV	4.2 kV	4.4 kV	4.4 kV	1.4 kV	1.5 kV	1.5 kV
4	1	None	1.36 MV (T1), 1.31 MV (T2), 1.51 MV (T3), 1.6 MV (T4)	1.41 MV	963.6 kV	552.2 kV	66.4 kV	70.7 kV	69.9 kV	5.1 kV	5.3 kV	5.2 kV	2.3 kV	2.4 kV	2.3 kV
		400 kV (All Phases)	764.9 kV (T1), 840 kV (T2), 1.01 MV (T3), 966 kV (T4)	920.4 kV	557.8 kV	323.2 kV	37.5 kV	40 kV	39.6 kV	3.7 kV	3.8 kV	3.7 kV	2.3 kV	2.4 kV	2.3 kV
		400 kV (Phase A)	764.9 kV (T1), 840 kV (T2), 1.01 MV (T3), 966 kV (T4)	920.4 kV	548.1 kV	323.3 kV	37.5 kV	40 kV	39.6 kV	3.7 kV	3.8 kV	3.7 kV	2.3 kV	2.4 kV	2.3 kV
	2	None	1.31 MV (T1), 1.45 MV (T2), 1.48 MV (T3), 1.4 MV (T4)	1.35 MV	914.8 kV	507.2 kV	63.4 kV	67.5 kV	66.7 kV	4 kV	4.2 kV	4.2 kV	1.3 kV	1.4 kV	1.4 kV
		400 kV (All Phases)	1.05 MV (T1), 965.1 kV (T2), 1.26 MV (T3), 1.06 MV (T4)	854.8 kV	611.7 kV	359.2 kV	40.1 kV	42.8 kV	42.3 kV	3.9 kV	4.1 kV	4.1 kV	1.3 kV	1.4 kV	1.4 kV
		400 kV (Phase A)	917.5 kV (T1), 965.3 kV (T2), 1.26 MV (T3), 1.06 MV (T4)	854.8 kV	614.5 kV	360.5 kV	40.1 kV	42.9 kV	42.4 kV	3.9 kV	4.1 kV	4.1 kV	1.3 kV	1.4 kV	1.4 kV
	3	None	1.52 MV (T1), 1.5 MV (T2), 1.49 MV (T3), 1.56 MV (T4)	1.46 MV	1.06 MV	588.1 kV	71 kV	75.8 kV	74.9 kV	3.5 kV	3.7 kV	3.6 kV	1.1 kV	1.2 kV	1.1 kV
		400 kV (All Phases)	1.02 MV (T1), 1.3 MV (T2), 1.09 MV (T3), 1.19 MV (T4)	820 kV	703.1 kV	436.1 kV	44.8 kV	48.1 kV	47.5 kV	3.5 kV	3.7 kV	3.6 kV	1.1 kV	1.2 kV	1.1 kV
		400 kV (Phase A)	1.02 MV (T1), 1.3 MV (T2), 1.09 MV (T3), 1.19 MV (T4)	823.6 kV	759 kV	455 kV	46.6 kV	50.1 kV	49.5 kV	3.5 kV	3.7 kV	3.6 kV	1.1 kV	1.2 kV	1.1 kV
	4	None	1.52 MV (T1), 1.39 MV (T2), 1.5 MV (T3), 1.59 MV (T4)	1.45 MV	1.10 MV	621.6 kV	72.6 kV	77.7 kV	76.7 kV	4.2 kV	4.5 kV	4.5 kV	1.2 kV	1.3 kV	1.3 kV
		400 kV (All Phases)	1.19 MV (T1), 1.05 MV (T2), 1.13 MV (T3), 1.22 MV (T4)	872.3 kV	748 kV	479 kV	46.4 kV	49.9 kV	49.3 kV	3.8 kV	4 kV	4 kV	1.2 kV	1.3 kV	1.3 kV
		400 kV (Phase A)	1.19 MV (T1), 1.05 MV (T2), 1.13 MV (T3), 1.22 MV (T4)	872.7 kV	802.2 kV	506.4 kV	47.6 kV	51.3 kV	50.7 kV	3.8 kV	4 kV	4 kV	1.2 kV	1.3 kV	1.3 kV

Figure 4.13: Results for 20 kA 1.2/50 μs direct stroke to the Phase A conductor without a surge capacitance.

- As a result, the surge arresters in 15.75 kV and 6 kV level don't affect the voltage levels significantly if 400 kV surge arresters are operating. One surge arrester operation in Phase A of 400 kV level (Case 3) is sufficient to make the system safe as each voltage level is below BIL.

4.3.4 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase A Conductor With a Surge Capacitance

In this part, the lightning source has been adjusted as 20 kA 1.2/50 μs and the Phase A conductor of the tower was exposed to lightning stroke. A surge capacitance of 0.36 μF is used in the network. The results are demonstrated in Figure 4.14 on the next page.

For the results of different cases and scenarios in Figure 4.14, following discussions and comments can be made:

- For all scenarios, the values in 400 kV level are almost the same as the case without a surge capacitance; whereas, the values in 15.75 kV and 6 kV level are significantly less than the case without a surge capacitance.
- When the lightning strikes to Phase A conductor of the towers without the operation of any surge arresters (Case 1), in case of 1 existing tower, Phase A and Phase B of 400 kV level are above BIL. In case of 2 and 3 existing towers, Phase A of 400 kV level is above BIL. In case of 4 existing towers, all phases of 400 kV level are below BIL. Except for 1 existing tower scenario, all phases of 15.75 kV level are below BIL. Moreover, all phases of 6 kV level are below BIL for all scenarios.
- As the number of towers increase, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage on each level is below BIL.
- When one surge arrester in Phase A of 400 kV level is operating (Case 3), the results are almost the same as the results in Case 2. Induced voltage on each level is below BIL.
- As a result, one surge arrester operation in Phase A of 400 kV level (Case 3) is sufficient to make the system safe as each voltage level is below BIL.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 15.75 kV Side			Induced Voltage Peak on 6 kV Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	3.05 MV (T1)	3.04 MV	2.07 MV	1.15 MV	74 kV	83.7 kV	81.8 kV	2.8 kV	3 kV	3 kV	1.2 kV	1.3 kV	1.2 kV
		400 kV (All Phases)	914.4 kV (T1)	943.2 kV	562.7 kV	306 kV	20.2 kV	22.7 kV	22.2 kV	2 kV	2.2 kV	2.1 kV	1.2 kV	1.3 kV	1.2 kV
		400 kV (Phase A)	914.4 kV (T1)	943.2 kV	563.2 kV	306.3 kV	20.2 kV	22.7 kV	22.2 kV	2 kV	2.2 kV	2.1 kV	1.2 kV	1.3 kV	1.2 kV
2	1	None	2.16 MV (T1), 2.2 MV (T2)	2.12 MV	1.48 MV	820.5 kV	52.5 kV	59.5 kV	58.2 kV	2.6 kV	2.8 kV	2.8 kV	1.2 kV	1.2 kV	1.2 kV
		400 kV (All Phases)	939.5 kV (T1), 1 MV (T2)	918.9 kV	610.8 kV	359.7 kV	20.8 kV	23.7 kV	23.2 kV	1.9 kV	2.1 kV	2.1 kV	1.2 kV	1.2 kV	1.2 kV
		400 kV (Phase A)	939.6 kV (T1), 1.03 MV (T2)	918.9 kV	612.6 kV	360.7 kV	20.8 kV	23.7 kV	23.2 kV	1.9 kV	2.1 kV	2.1 kV	1.2 kV	1.2 kV	1.2 kV
	2	None	2.19 MV (T1), 2.38 MV (T2)	2.19 MV	1.48 MV	810.4 kV	53.2 kV	60.1 kV	58.8 kV	2.6 kV	3 kV	2.9 kV	0.9 kV	1 kV	1 kV
		400 kV (All Phases)	1.22 MV (T1), 1.11 MV (T2)	944.7 kV	729.3 kV	418.7 kV	23 kV	26.5 kV	25.8 kV	2.3 kV	2.6 kV	2.5 kV	0.8 kV	0.9 kV	0.9 kV
		400 kV (Phase A)	1.22 MV (T1), 1.11 MV (T2)	945.1 kV	766.5 kV	440.3 kV	23.6 kV	27.2 kV	26.5 kV	2.3 kV	2.6 kV	2.5 kV	0.8 kV	0.9 kV	0.9 kV
3	1	None	1.66 MV (T1), 1.62 MV (T2), 1.76 MV (T3)	1.7 MV	1.17 MV	663.7 kV	41.8 kV	47.3 kV	46.3 kV	2.6 kV	2.8 kV	2.7 kV	1.2 kV	1.2 kV	1.2 kV
		400 kV (All Phases)	866.7 kV (T1), 996.2 kV (T2), 1.04 MV (T3)	920.4 kV	596.9 kV	352 kV	20.7 kV	23.6 kV	23.1 kV	1.9 kV	2.1 kV	2.1 kV	1.2 kV	1.2 kV	1.2 kV
		400 kV (Phase A)	866.8 kV (T1), 996.2 kV (T2), 1.04 kV (T3)	917.7 kV	597.8 kV	352.3 kV	20.7 kV	23.6 kV	23.1 kV	1.9 kV	2.1 kV	2.1 kV	1.2 kV	1.2 kV	1.2 kV
	2	None	1.63 MV (T1), 1.75 MV (T2), 1.77 MV (T3)	1.63 MV	1.12 MV	624.2 kV	40 kV	45.3 kV	44.3 kV	2.1 kV	2.3 kV	2.3 kV	0.7 kV	0.8 kV	0.8 kV
		400 kV (All Phases)	1.04 MV (T1), 1.26 MV (T2), 1.1 MV (T3)	867.6 kV	687.4 kV	400 kV	22.9 kV	26.2 kV	25.7 kV	2.1 kV	2.3 kV	2.3 kV	0.7 kV	0.8 kV	0.8 kV
		400 kV (Phase A)	1.04 MV (T1), 1.26 MV (T2), 1.1 MV (T3)	867.6 kV	724.9 kV	425.5 kV	23.5 kV	27 kV	26.4 kV	2.1 kV	2.3 kV	2.3 kV	0.7 kV	0.8 kV	0.8 kV
	3	None	1.69 MV (T1), 1.7 MV (T2), 1.85 MV (T3)	1.67 MV	1.19 MV	647.5 kV	41.3 kV	46.9 kV	45.9 kV	2.4 kV	2.8 kV	2.7 kV	0.8 kV	0.9 kV	0.8 kV
		400 kV (All Phases)	1.25 MV (T1), 1.08 MV (T2), 1.15 MV (T3)	910.3 kV	757.4 kV	471 kV	24.1 kV	27.8 kV	27.2 kV	2.4 kV	2.8 kV	2.7 kV	0.8 kV	0.9 kV	0.8 kV
		400 kV (Phase A)	1.25 MV (T1), 1.08 MV (T2), 1.15 MV (T3)	910.9 kV	815.4 kV	504.2 kV	24.9 kV	28.8 kV	28.1 kV	2.4 kV	2.8 kV	2.7 kV	0.8 kV	0.9 kV	0.8 kV
4	1	None	1.36 MV (T1), 1.31 MV (T2), 1.51 MV (T3), 1.6 MV (T4)	1.41 MV	961 kV	550.6 kV	34.4 kV	39 kV	38.2 kV	2.6 kV	2.8 kV	2.7 kV	1.2 kV	1.2 kV	1.2 kV
		400 kV (All Phases)	764.9 kV (T1), 840 kV (T2), 1.01 MV (T3), 966 kV (T4)	917.7 kV	547.8 kV	323.3 kV	19.5 kV	22.1 kV	21.7 kV	2.6 kV	2.8 kV	2.7 kV	1.2 kV	1.2 kV	1.2 kV
		400 kV (Phase A)	764.9 kV (T1), 840 kV (T2), 1.01 MV (T3), 966 kV (T4)	917.7 kV	548.2 kV	323.4 kV	19.5 kV	22.1 kV	21.7 kV	2.6 kV	2.8 kV	2.7 kV	1.2 kV	1.2 kV	1.2 kV
	2	None	1.31 MV (T1), 1.45 MV (T2), 1.48 MV (T3), 1.4 MV (T4)	1.35 MV	914 kV	506.1 kV	32.9 kV	37.2 kV	36.4 kV	2 kV	2.3 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
		400 kV (All Phases)	1.05 MV (T1), 965.1 kV (T2), 1.26 MV (T3), 1.06 MV (T4)	853.8 kV	612.6 kV	359.8 kV	20.9 kV	23.7 kV	23.2 kV	2 kV	2.3 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
		400 kV (Phase A)	917.5 kV (T1), 965.3 kV (T2), 1.26 MV (T3), 1.06 MV (T4)	853.8 kV	615.5 kV	361.1 kV	20.9 kV	23.7 kV	23.2 kV	2 kV	2.3 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
	3	None	1.52 MV (T1), 1.5 MV (T2), 1.49 MV (T3), 1.56 MV (T4)	1.46 MV	1.06 MV	587.6 kV	36.9 kV	41.9 kV	41 kV	1.8 kV	2 kV	2 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV (All Phases)	1.02 MV (T1), 1.3 MV (T2), 1.09 MV (T3), 1.19 MV (T4)	818.8 kV	703.1 kV	436.9 kV	23.3 kV	26.7 kV	26.2 kV	1.8 kV	2 kV	2 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV (Phase A)	1.02 MV (T1), 1.3 MV (T2), 1.09 MV (T3), 1.19 MV (T4)	823.1 kV	759.2 kV	455.6 kV	24.2 kV	27.9 kV	27.3 kV	1.8 kV	2 kV	2 kV	0.6 kV	0.6 kV	0.6 kV
	4	None	1.52 MV (T1), 1.39 MV (T2), 1.5 MV (T3), 1.59 MV (T4)	1.45 MV	1.10 MV	619 kV	37.6 kV	42.8 kV	41.9 kV	2.2 kV	2.5 kV	2.4 kV	0.6 kV	0.7 kV	0.6 kV
		400 kV (All Phases)	1.19 MV (T1), 1.05 MV (T2), 1.13 MV (T3), 1.22 MV (T4)	869.4 kV	746.8 kV	480.1 kV	24.1 kV	27.7 kV	27.1 kV	2.2 kV	2.5 kV	2.4 kV	0.6 kV	0.7 kV	0.6 kV
		400 kV (Phase A)	1.19 MV (T1), 1.05 MV (T2), 1.13 MV (T3), 1.22 MV (T4)	869.7 kV	802.7 kV	506.3 kV	24.7 kV	28.5 kV	27.9 kV	2.2 kV	2.5 kV	2.4 kV	0.6 kV	0.7 kV	0.6 kV

Figure 4.14: Results for 20 kA 1.2/50 μs direct stroke to the Phase A conductor with a surge capacitance.

4.3.5 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase B Conductor Without a Surge Capacitance

In this part, the lightning source has been adjusted as 20 kA 1.2/50 μs and the Phase B conductor of the tower was exposed to lightning stroke. No surge capacitance is used in the network. The results are demonstrated in Figure 4.15 on the next page.

For the results of different cases and scenarios in Figure 4.15, following discussions and comments can be made:

- When the lightning strikes to Phase B conductor of the towers without the operation of any surge arresters (Case 1), in case of 1 existing tower, the magnitudes of the induced voltages on Phase A and Phase B of 400 kV level are above BIL. In case of 2 existing towers, if the lightning strikes to the second tower, the magnitude of the induced voltage on Phase B of 400 kV level is above BIL. For the other scenarios, all phases of 400 kV level are below BIL.

- When the lightning strikes to Phase B conductor of the towers without any protection (Case 1), in case of 1, 2, and 3 existing towers, the magnitudes of the induced voltages on all phases of 15.75 kV level are above BIL. In case of 4 existing towers, the magnitudes of the induced voltages on all phases of 15.75 kV level are below BIL. Moreover, all phases of 6 kV level are below BIL for all scenarios.

- As the number of towers increase, the magnitude of the induced voltages on each level decreases.

- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases generally; however, the magnitude is still less than the scenario with the fewer towers.

- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage on each level is below BIL.

- When one surge arrester in Phase B of 400 kV level is operating (Case 6), the results are slightly higher than Case 2 for Phase A of 400 kV level and all phases of 15.75 kV level; whereas, Phase B and Phase C of 400 kV level are almost same. Induced voltage on each level is below BIL.

- As a result, one surge arrester operation in Phase B of 400 kV level (Case 6) is sufficient to make the system safe as each voltage level is below BIL.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 15.75 kV Side			Induced Voltage Peak on 6 kV Side			Induced Voltage Peak on 400 V Side		
				Phase B	Phase B	Phase C	Phase B	Phase B	Phase C	Phase B	Phase B	Phase C	Phase B	Phase B	Phase C
1	1	None	2.37 MV (T1)	2.37 MV	2.4 MV	1.33 MV	139.2 kV	150.1 kV	148 kV	5.7 kV	6.3 kV	6.1 kV	2.5 kV	2.8 kV	2.6 kV
		400 kV (All Phases)	702.2 kV (T1)	695.6 kV	888 kV	452.3 kV	44.6 kV	48.3 kV	47.6 kV	4.6 kV	5 kV	4.9 kV	2.5 kV	2.8 kV	2.6 kV
		400 kV (Phase B)	796.1 kV (T1)	794.1 kV	888 kV	454.3 kV	46.7 kV	50.3 kV	49.7 kV	4.6 kV	5 kV	4.9 kV	2.5 kV	2.8 kV	2.6 kV
2	1	None	1.62 MV (T1), 1.61 MV (T2)	1.61 MV	1.58 MV	889.4 kV	93.4 kV	100.6 kV	99.3 kV	5.3 kV	5.9 kV	5.7 kV	2.4 kV	2.7 kV	2.6 kV
		400 kV (All Phases)	795.7 kV (T1), 788.2 kV (T2)	739.4 kV	868.1 kV	455.1 kV	45.1 kV	48.7 kV	48 kV	4.4 kV	4.8 kV	4.7 kV	2.4 kV	2.7 kV	2.6 kV
		400 kV (Phase B)	872.8 kV (T1), 849 kV (T2)	853.1 kV	868.1 kV	459.9 kV	47.8 kV	51.4 kV	50.8 kV	4.4 kV	4.8 kV	4.7 kV	2.4 kV	2.7 kV	2.6 kV
	2	None	1.64 MV (T1), 1.72 MV (T2)	1.62 MV	1.64 MV	891.1 kV	94.8 kV	102.3 kV	100.8 kV	4.8 kV	5.2 kV	5.1 kV	1.7 kV	1.8 kV	1.8 kV
		400 kV (All Phases)	792.5 kV (T1), 909.9 kV (T2)	794.5 kV	848 kV	603.8 kV	51.4 kV	55.5 kV	55 kV	4.6 kV	4.9 kV	4.9 kV	1.7 kV	1.8 kV	1.8 kV
		400 kV (Phase B)	904.5 kV (T1), 1.1 MV (T2)	953.2 kV	862.3 kV	609.6 kV	55.2 kV	59.4 kV	58.9 kV	4.6 kV	4.9 kV	4.9 kV	1.7 kV	1.8 kV	1.8 kV
3	1	None	1.25 MV (T1), 1.2 MV (T2), 1.27 MV (T3)	1.24 MV	1.23 MV	659.9 kV	71.5 kV	77.1 kV	76 kV	5.3 kV	5.9 kV	5.7 kV	2.4 kV	2.7 kV	2.6 kV
		400 kV (All Phases)	783.8 kV (T1), 798.3 kV (T2), 820.9 kV (T3)	723.6 kV	867.5 kV	413 kV	43.4 kV	46.9 kV	46.2 kV	4.4 kV	4.8 kV	4.7 kV	2.4 kV	2.7 kV	2.6 kV
		400 kV (Phase B)	850.5 kV (T1), 799.7 kV (T2), 820.9 kV (T3)	820 kV	867.5 kV	419.8 kV	45.7 kV	49.2 kV	48.5 kV	4.4 kV	4.8 kV	4.7 kV	2.4 kV	2.7 kV	2.6 kV
	2	None	1.21 MV (T1), 1.29 MV (T2), 1.31 MV (T3)	1.21 MV	1.22 MV	671.6 kV	70.2 kV	75.7 kV	74.7 kV	3.8 kV	4.1 kV	4.1 kV	1.3 kV	1.4 kV	1.4 kV
		400 kV (All Phases)	801.7 kV (T1), 1.02 MV (T2), 786.8 kV (T3)	740.8 kV	790.2 kV	492.6 kV	45.5 kV	49.1 kV	48.6 kV	3.8 kV	4.1 kV	4.1 kV	1.3 kV	1.4 kV	1.4 kV
		400 kV (Phase B)	898.4 kV (T1), 1.04 MV (T2), 934.9 kV (T3)	904.9 kV	793 kV	496.8 kV	49.8 kV	53.5 kV	52.9 kV	3.8 kV	4.1 kV	4.1 kV	1.3 kV	1.4 kV	1.4 kV
	3	None	1.25 MV (T1), 1.24 MV (T2), 1.42 MV (T3)	1.27 MV	1.24 MV	748.4 kV	73.1 kV	78.7 kV	77.7 kV	4.2 kV	4.5 kV	4.5 kV	1.3 kV	1.4 kV	1.4 kV
		400 kV (All Phases)	890.8 kV (T1), 829.8 kV (T2), 829.2 kV (T3)	814.6 kV	816.6 kV	594.4 kV	50.2 kV	54.1 kV	53.6 kV	3.8 kV	4.1 kV	4.1 kV	1.3 kV	1.4 kV	1.4 kV
		400 kV (Phase B)	1.02 MV (T1), 930.6 kV (T2), 996.7 kV (T3)	1.05 MV	837.2 kV	609.6 kV	55.9 kV	59.8 kV	59.5 kV	4 kV	4.3 kV	4.3 kV	1.3 kV	1.4 kV	1.4 kV
4	1	None	1.04 MV (T1), 972.6 kV (T2), 1.06 MV (T3), 1.16 MV (T4)	1.02 MV	1.15 MV	517.1 kV	57.9 kV	62.4 kV	61.4 kV	5.3 kV	5.9 kV	5.7 kV	2.4 kV	2.7 kV	2.6 kV
		400 kV (All Phases)	737.4 kV (T1), 722 kV (T2), 781 kV (T3), 794.1 kV (T4)	695.6 kV	867.5 kV	377.8 kV	41.4 kV	44.8 kV	44.1 kV	4.4 kV	4.8 kV	4.7 kV	2.4 kV	2.7 kV	2.6 kV
		400 kV (Phase B)	770.1 kV (T1), 754.6 kV (T2), 781 kV (T3), 794.1 kV (T4)	753.7 kV	867.5 kV	383.6 kV	43 kV	46.3 kV	45.6 kV	4.4 kV	4.8 kV	4.7 kV	2.4 kV	2.7 kV	2.6 kV
	2	None	990.8 kV (T1), 1.09 MV (T2), 1.1 MV (T3), 1.03 MV (T4)	966.3 kV	1 MV	524.8 kV	56.3 kV	60.9 kV	60 kV	3.8 kV	4.1 kV	4 kV	1.3 kV	1.4 kV	1.4 kV
		400 kV (All Phases)	753.4 kV (T1), 848 kV (T2), 976.3 kV (T3), 787.2 kV (T4)	713.1 kV	767 kV	453.5 kV	42.8 kV	46.4 kV	45.8 kV	3.8 kV	4.1 kV	4 kV	1.3 kV	1.4 kV	1.4 kV
		400 kV (Phase B)	801.4 kV (T1), 900.4 kV (T2), 981.1 kV (T3), 817.1 kV (T4)	789.1 kV	767.9 kV	453.3 kV	44.7 kV	48.2 kV	47.5 kV	3.8 kV	4.1 kV	4 kV	1.3 kV	1.4 kV	1.4 kV
	3	None	1.07 MV (T1), 1.05 MV (T2), 1.12 MV (T3), 1.18 MV (T4)	1.08 MV	1.06 MV	631.3 kV	63.3 kV	68.2 kV	67.4 kV	3 kV	3.2 kV	3.2 kV	1 kV	1 kV	1 kV
		400 kV (All Phases)	830.3 kV (T1), 1.01 MV (T2), 792.3 kV (T3), 765.9 kV (T4)	751.4 kV	746.8 kV	515 kV	45.9 kV	49.5 kV	49.1 kV	3 kV	3.2 kV	3.2 kV	1 kV	1 kV	1 kV
		400 kV (Phase B)	973.8 kV (T1), 1.04 MV (T2), 917.3 kV (T3), 918.3 kV (T4)	962.1 kV	765.8 kV	526.2 kV	51.5 kV	55.1 kV	54.7 kV	3 kV	3.2 kV	3.2 kV	1 kV	1 kV	1 kV
	4	None	1.06 MV (T1), 1.02 MV (T2), 1.13 MV (T3), 1.2 MV (T4)	1.09 MV	1.02 MV	648.7 kV	63 kV	67.8 kV	67.1 kV	3.6 kV	3.9 kV	3.8 kV	1 kV	1.1 kV	1.1 kV
		400 kV (All Phases)	917.8 kV (T1), 771.9 kV (T2), 823.6 kV (T3), 784.6 kV (T4)	807.7 kV	745.8 kV	542.9 kV	46.7 kV	50.3 kV	49.8 kV	3.6 kV	3.9 kV	3.8 kV	1 kV	1.1 kV	1.1 kV
		400 kV (Phase B)	1.02 MV (T1), 864.6 kV (T2), 948.7 kV (T3), 995.7 kV (T4)	1.02 MV	784.7 kV	558 kV	54.1 kV	57.9 kV	57.5 kV	3.6 kV	3.9 kV	3.8 kV	1 kV	1.1 kV	1.1 kV

Figure 4.15: Results for 20 kA 1.2/50 μs direct stroke to the Phase B conductor without a surge capacitance.

4.3.6 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase B Conductor With a Surge Capacitance

In this part, the lightning source has been adjusted as 20 kA 1.2/50 μs and the Phase B conductor of the tower was exposed to lightning stroke. A surge capacitance of 0.36 μF is used in the network. The results are demonstrated in Figure 4.16 on the next page.

For the results of different cases and scenarios in Figure 4.16, following discussions and comments can be made:

- For all scenarios, the values in 400 kV level are almost the same as the case without a surge capacitance; whereas, the values in 15.75 kV and 6 kV level are significantly less than the case without a surge capacitance.
- When the lightning strikes to Phase B conductor of the towers without the operation of any surge arresters (Case 1), in case of 1 existing tower, the magnitudes of the induced voltages on Phase A and Phase B of 400 kV level are above BIL. In case of 2 existing towers, if the lightning strikes to the second tower, the magnitude of the induced voltage on Phase B of 400 kV level is above BIL. For the other scenarios, all phases of 400 kV level are below BIL. Except for 1 existing tower scenario, all phases of 15.75 kV level are below BIL. Moreover, all phases of 6 kV level are below BIL for all scenarios.
- As the number of towers increase, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases generally; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage on each level is below BIL.
- When one surge arrester in Phase B of 400 kV level is operating (Case 6), the results are slightly higher than Case 2 for Phase A of 400 kV level and all phases of 15.75 kV level; whereas, Phase B and Phase C of 400 kV level are almost same. Induced voltage on each level is below BIL.
- As a result, one surge arrester operation in Phase B of 400 kV level (Case 6) is sufficient to make the system safe as each voltage level is below BIL.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 15.75 kV Side			Induced Voltage Peak on 6 kV Side			Induced Voltage Peak on 400 V Side		
				Phase B	Phase B	Phase C	Phase B	Phase B	Phase C	Phase B	Phase B	Phase C	Phase B	Phase B	Phase C
1	1	None	2.37 MV (T1)	2.37 MV	2.39 MV	1.32 MV	72.1 kV	83.5 kV	81.4 kV	2.9 kV	3.5 kV	3.4 kV	1.2 kV	1.6 kV	1.4 kV
		400 kV (All Phases)	702.2 kV (T1)	695.6 kV	884.3 kV	450.4 kV	23.1 kV	27 kV	26.3 kV	2.4 kV	2.8 kV	2.7 kV	1.2 kV	1.6 kV	1.4 kV
		400 kV (Phase B)	796.1 kV (T1)	793.2 kV	884.3 kV	453.8 kV	24.3 kV	28.1 kV	27.4 kV	2.4 kV	2.8 kV	2.7 kV	1.2 kV	1.6 kV	1.4 kV
2	1	None	1.62 MV (T1), 1.61 MV (T2)	1.61 MV	1.58 MV	887.5 kV	48.4 kV	55.9 kV	54.6 kV	2.7 kV	3.3 kV	3.1 kV	1.2 kV	1.5 kV	1.4 kV
		400 kV (All Phases)	795.7 kV (T1), 788.2 kV (T2)	738.6 kV	864.5 kV	455.5 kV	23.4 kV	27.2 kV	26.5 kV	2.3 kV	2.7 kV	2.6 kV	1.2 kV	1.5 kV	1.4 kV
		400 kV (Phase B)	872.8 kV (T1), 849 kV (T2)	851.9 kV	864.5 kV	459.9 kV	24.8 kV	28.6 kV	28 kV	2.3 kV	2.7 kV	2.6 kV	1.2 kV	1.5 kV	1.4 kV
	2	None	1.64 MV (T1), 1.72 MV (T2)	1.61 MV	1.64 MV	888.6 kV	49.1 kV	56.8 kV	55.4 kV	2.5 kV	2.9 kV	2.8 kV	0.9 kV	1 kV	1 kV
		400 kV (All Phases)	792.5 kV (T1), 909.9 kV (T2)	795.7 kV	850.5 kV	601.7 kV	26.7 kV	31 kV	30.5 kV	2.3 kV	2.7 kV	2.7 kV	0.9 kV	1 kV	1 kV
		400 kV (Phase B)	904.5 kV (T1), 1.1 MV (T2)	952.3 kV	864 kV	606.6 kV	28.6 kV	33 kV	32.5 kV	2.3 kV	2.7 kV	2.7 kV	0.9 kV	1 kV	1 kV
3	1	None	1.25 MV (T1), 1.2 MV (T2), 1.27 MV (T3)	1.23 MV	1.23 MV	659.1 kV	37.1 kV	42.9 kV	41.8 kV	2.7 kV	3.3 kV	3.2 kV	1.2 kV	1.6 kV	1.4 kV
		400 kV (All Phases)	783.8 kV (T1), 798.3 kV (T2), 820.9 kV (T3)	723.6 kV	863.9 kV	413.6 kV	22.6 kV	26.2 kV	25.5 kV	2.3 kV	2.7 kV	2.6 kV	1.2 kV	1.6 kV	1.4 kV
		400 kV (Phase B)	850.5 kV (T1), 799.7 kV (T2), 820.9 kV (T3)	821.2 kV	863.9 kV	419.9 kV	23.7 kV	27.4 kV	26.7 kV	2.3 kV	2.7 kV	2.6 kV	1.2 kV	1.6 kV	1.4 kV
	2	None	1.21 MV (T1), 1.29 MV (T2), 1.31 MV (T3)	1.21 MV	1.22 MV	670.6 kV	36.5 kV	42.2 kV	41.1 kV	2 kV	2.3 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
		400 kV (All Phases)	801.7 kV (T1), 1.02 MV (T2), 786.8 kV (T3)	741 kV	790.2 kV	493.4 kV	23.6 kV	27.4 kV	26.9 kV	2 kV	2.3 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
		400 kV (Phase B)	898.4 kV (T1), 1.04 MV (T2), 934.9 kV (T3)	904 kV	792.8 kV	497.7 kV	25.9 kV	29.7 kV	29.1 kV	2 kV	2.3 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
	3	None	1.25 MV (T1), 1.24 MV (T2), 1.42 MV (T3)	1.26 MV	1.24 MV	745.2 kV	37.9 kV	43.8 kV	42.7 kV	2.2 kV	2.5 kV	2.4 kV	0.7 kV	0.8 kV	0.7 kV
		400 kV (All Phases)	890.8 kV (T1), 829.8 kV (T2), 829.2 kV (T3)	815.2 kV	816.5 kV	595.6 kV	26 kV	30.1 kV	29.6 kV	2 kV	2.3 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
		400 kV (Phase B)	1.02 MV (T1), 930.6 kV (T2), 996.7 kV (T3)	1.04 MV	836.1 kV	609.6 kV	29.1 kV	33.2 kV	32.8 kV	2 kV	2.3 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
4	1	None	1.04 MV (T1), 972.6 kV (T2), 1.06 MV (T3), 1.16 MV (T4)	1.01 MV	1.14 MV	516.6 kV	30 kV	34.1 kV	33.7 kV	2.7 kV	3.3 kV	3.1 kV	1.2 kV	1.5 kV	1.4 kV
		400 kV (All Phases)	737.4 kV (T1), 722 kV (T2), 781 kV (T3), 794.1 kV (T4)	695 kV	863.9 kV	378 kV	21.5 kV	25 kV	24.3 kV	2.3 kV	2.7 kV	2.6 kV	1.2 kV	1.5 kV	1.4 kV
		400 kV (Phase B)	770.1 kV (T1), 754.6 kV (T2), 781 kV (T3), 794.1 kV (T4)	753.8 kV	863.9 kV	383.5 kV	22.3 kV	25.8 kV	25.1 kV	2.3 kV	2.7 kV	2.6 kV	1.2 kV	1.5 kV	1.4 kV
	2	None	990.8 kV (T1), 1.09 MV (T2), 1.1 MV (T3), 1.03 MV (T4)	963.8 kV	1 MV	525 kV	29.3 kV	34 kV	33.1 kV	1.9 kV	2.2 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
		400 kV (All Phases)	753.4 kV (T1), 848 kV (T2), 976.3 kV (T3), 787.2 kV (T4)	713.4 kV	766.8 kV	450.8 kV	22.3 kV	25.9 kV	25.3 kV	1.9 kV	2.2 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
		400 kV (Phase B)	801.4 kV (T1), 900.4 kV (T2), 981.1 kV (T3), 817.1 kV (T4)	788.5 kV	676.6 kV	451 kV	23.2 kV	26.8 kV	26.2 kV	1.9 kV	2.2 kV	2.2 kV	0.7 kV	0.8 kV	0.7 kV
	3	None	1.07 MV (T1), 1.05 MV (T2), 1.12 MV (T3), 1.18 MV (T4)	1.07 MV	1.06 MV	630.7 kV	32.9 kV	38 kV	37.1 kV	1.6 kV	1.8 kV	1.7 kV	0.5 kV	0.6 kV	0.6 kV
		400 kV (All Phases)	830.3 kV (T1), 1.01 MV (T2), 792.3 kV (T3), 765.9 kV (T4)	752.5 kV	748.1 kV	516.1 kV	23.9 kV	27.7 kV	27.2 kV	1.6 kV	1.8 kV	1.7 kV	0.5 kV	0.6 kV	0.6 kV
		400 kV (Phase B)	973.8 kV (T1), 1.04 MV (T2), 917.3 kV (T3), 918.3 kV (T4)	962.2 kV	766.7 kV	526.9 kV	26.8 kV	30.6 kV	30.1 kV	1.6 kV	1.8 kV	1.7 kV	0.5 kV	0.6 kV	0.6 kV
	4	None	1.06 MV (T1), 1.02 MV (T2), 1.13 MV (T3), 1.2 MV (T4)	1.09 MV	1.02 MV	648.4 kV	32.6 kV	37.6 kV	36.9 kV	1.9 kV	2.1 kV	2.1 kV	0.5 kV	0.6 kV	0.6 kV
		400 kV (All Phases)	917.8 kV (T1), 771.9 kV (T2), 823.6 kV (T3), 784.6 kV (T4)	807.2 kV	747.7 kV	542.5 kV	24.2 kV	27.9 kV	27.4 kV	1.9 kV	2.1 kV	2.1 kV	0.5 kV	0.6 kV	0.6 kV
		400 kV (Phase B)	1.02 MV (T1), 864.6 kV (T2), 948.7 kV (T3), 995.7 kV (T4)	1.02 MV	785.5 kV	556.2 kV	28.1 kV	32 kV	31.6 kV	1.9 kV	2.1 kV	2.1 kV	0.5 kV	0.6 kV	0.6 kV

Figure 4.16: Results for 20 kA 1.2/50 μs direct stroke to the Phase B conductor with a surge capacitance.

4.3.7 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase C Conductor Without a Surge Capacitance

In this part, lightning source has been adjusted as 20 kA 1.2/50 μs and the Phase C conductor of the tower was exposed to lightning stroke. No surge capacitance is used in the network. The results are demonstrated in Figure 4.17 on the next page.

For the results of different cases and scenarios in Figure 4.17, following discussions and comments can be made:

- When the lightning strikes to Phase C conductor without the operation of any surge arresters (Case 1), all phases of 400 kV level are below BIL.
- When the lightning strikes to Phase C conductor without the operation of any surge arresters (Case 1), in case of 1 and 2 existing towers, Phase B and Phase C of 15.75 kV level are above BIL. Phase A of 15.75 kV level is above for 1 existing tower scenario. Moreover, all phases of 6 kV level are below BIL for all scenarios.
- As the number of towers increase, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases generally; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage on each level reduces. All phases of each level are below BIL.
- When one surge arrester in Phase C of 400 kV level is operating (Case 7), the results are slightly higher than Case 2 for Phase A and Phase B of 400 kV level and all phases of 15.75 kV level; whereas, Phase C of 400 kV level is almost same. Induced voltage on each level is below BIL.
- As a result, one surge arrester operation in Phase C of 400 kV level (Case 7) is sufficient to make the system safe as each voltage level is below BIL.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 15.75 kV Side			Induced Voltage Peak on 6 kV Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	1.5 MV (T1)	1.5 MV	1.52 MV	1.62 MV	104.4 kV	112.7 kV	112.8 kV	4.6 kV	5 kV	5.1 kV	2.2 kV	2.4 kV	2.5 kV
		400 kV (All Phases)	643.8 kV (T2)	643.3 kV	678.5 kV	879.7 kV	48 kV	51.9 kV	52.1 kV	3.6 kV	4 kV	4.1 kV	2.2 kV	2.4 kV	2.5 kV
		400 kV (Phase C)	751 kV (T1)	752.8 kV	759.1 kV	879.7 kV	52 kV	56.1 kV	56.2 kV	3.6 kV	4 kV	4.1 kV	2.2 kV	2.4 kV	2.5 kV
2	1	None	961.5 kV (T1), 984.3 kV (T2)	971.2 kV	974.2 kV	1.05 MV	66.4 kV	71.5 kV	71.5 kV	4.3 kV	4.7 kV	4.8 kV	2.2 kV	2.3 kV	2.5 kV
		400 kV (All Phases)	673.6 kV (T1), 682.4 kV (T2)	668.3 kV	680.9 kV	858.6 kV	47.6 kV	51.4 kV	51.5 kV	3.5 kV	3.8 kV	3.9 kV	2.2 kV	2.3 kV	2.5 kV
		400 kV (Phase C)	748.7 kV (T1), 763.7 kV (T2)	747.6 kV	748.4 kV	858.6 kV	51 kV	55 kV	55 kV	3.5 kV	3.8 kV	3.9 kV	2.2 kV	2.3 kV	2.5 kV
	2	None	1.01 MV (T1), 1.05 MV (T2)	994.8 kV	974.9 kV	1.02 MV	67.2 kV	72.4 kV	72.5 kV	3.3 kV	3.6 kV	3.6 kV	1.2 kV	1.2 kV	1.3 kV
		400 kV (All Phases)	735.9 kV (T1), 795 kV (T2)	715.7 kV	707.6 kV	793.5 kV	49.3 kV	53.1 kV	53.2 kV	3.3 kV	3.5 kV	3.5 kV	1.2 kV	1.2 kV	1.3 kV
		400 kV (Phase C)	774 kV (T1), 833 kV (T2)	766.6 kV	763.7 kV	794.7 kV	52 kV	56 kV	56 kV	3.3 kV	3.5 kV	3.5 kV	1.2 kV	1.2 kV	1.3 kV
3	1	None	722.4 kV (T1), 717.4 kV (T2), 755.2 kV (T3)	730.2 kV	702.9 kV	1.05 MV	49.1 kV	52.9 kV	52.9 kV	4.3 kV	4.7 kV	4.8 kV	2.2 kV	2.3 kV	2.5 kV
		400 kV (All Phases)	648.5 kV (T1), 654.6 kV (T2), 664.8 kV (T3)	646.1 kV	632.9 kV	858.2 kV	43.7 kV	47.1 kV	47.2 kV	3.5 kV	3.8 kV	3.9 kV	2.2 kV	2.3 kV	2.5 kV
		400 kV (Phase C)	669.6 kV (T1), 667.9 kV (T2), 677.7 kV (T3)	669.8 kV	650.8 kV	858.2 kV	44.6 kV	48 kV	48 kV	3.5 kV	3.8 kV	3.9 kV	2.2 kV	2.3 kV	2.5 kV
	2	None	726 kV (T1), 771.9 kV (T2), 765.2 kV (T3)	728 kV	716.5 kV	771.3 kV	49.2 kV	53 kV	53 kV	2.7 kV	3 kV	3 kV	0.9 kV	1 kV	1 kV
		400 kV (All Phases)	663.8 kV (T1), 714.7 kV (T2), 721.4 kV (T3)	652.8 kV	655.9 kV	698.1 kV	45.5 kV	49.1 kV	49.2 kV	2.7 kV	3 kV	3 kV	0.9 kV	1 kV	1 kV
		400 kV (Phase C)	684.3 kV (T1), 735.6 kV (T2), 732 kV (T3)	686.8 kV	680.6 kV	699.5 kV	46.7 kV	50.4 kV	50.4 kV	2.7 kV	3 kV	3 kV	0.9 kV	1 kV	1 kV
	3	None	754.4 kV (T1), 731.1 kV (T2), 850.3 kV (T3)	753.9 kV	762.7 kV	739.2 kV	51.4 kV	55.4 kV	55.4 kV	2.8 kV	3 kV	3 kV	0.9 kV	0.9 kV	0.9 kV
		400 kV (All Phases)	678 kV (T1), 674.6 kV (T2), 779.1 kV (T3)	665.1 kV	699.5 kV	683.8 kV	45.8 kV	49.7 kV	49.7 kV	2.8 kV	3 kV	3 kV	0.9 kV	0.9 kV	0.9 kV
		400 kV (Phase C)	730.2 kV (T1), 707.4 kV (T2), 829.5 kV (T3)	726 kV	754.5 kV	694 kV	48.9 kV	52.7 kV	52.6 kV	2.8 kV	3 kV	3 kV	0.9 kV	0.9 kV	0.9 kV
4	1	None	613.2 kV (T1), 574 kV (T2), 599.3 kV (T3), 644.9 kV (T4)	602.8 kV	549.3 kV	1.05 MV	40.8 kV	44.5 kV	45.4 kV	4.3 kV	4.7 kV	4.8 kV	2.2 kV	2.3 kV	2.5 kV
		400 kV (All Phases)	548.2 kV (T1), 546.9 kV (T2), 539.3 kV (T3), 547.9 kV (T4)	544.9 kV	511.8 kV	858.2 kV	37.2 kV	40 kV	40.1 kV	3.5 kV	3.8 kV	3.9 kV	2.2 kV	2.3 kV	2.5 kV
		400 kV (Phase C)	548.5 kV (T1), 547.1 kV (T2), 539.7 kV (T3), 548.3 kV (T4)	545.4 kV	512.1 kV	858.2 kV	37.2 kV	40 kV	40.1 kV	3.5 kV	3.8 kV	3.9 kV	2.2 kV	2.3 kV	2.5 kV
	2	None	591.7 kV (T1), 643.3 kV (T2), 650.1 kV (T3), 598.5 kV (T4)	573.8 kV	550.5 kV	664.4 kV	39 kV	42.1 kV	42.2 kV	2.7 kV	2.9 kV	2.9 kV	0.9 kV	1 kV	1 kV
		400 kV (All Phases)	588.1 kV (T1), 639.2 kV (T2), 644.4 kV (T3), 596.3 kV (T4)	570.1 kV	546.9 kV	652.5 kV	38.7 kV	41.8 kV	41.9 kV	2.7 kV	2.9 kV	2.9 kV	0.9 kV	1 kV	1 kV
		400 kV (Phase C)	588.7 kV (T1), 639.6 kV (T2), 644.6 kV (T3), 596.8 kV (T4)	571.2 kV	547.5 kV	652.5 kV	38.7 kV	41.8 kV	41.9 kV	2.7 kV	2.9 kV	2.9 kV	0.9 kV	1 kV	1 kV
	3	None	601.2 kV (T1), 603.6 kV (T2), 657.2 kV (T3), 795.8 kV (T4)	610.3 kV	650.5 kV	605.6 kV	42.6 kV	46.1 kV	46 kV	2 kV	2.2 kV	2.2 kV	0.6 kV	0.7 kV	0.7 kV
		400 kV (All Phases)	599.3 kV (T1), 596.2 kV (T2), 649.6 kV (T3), 696.2 kV (T4)	607.6 kV	639.5 kV	600.6 kV	42.1 kV	45.5 kV	45.4 kV	2 kV	2.2 kV	2.2 kV	0.6 kV	0.7 kV	0.7 kV
		400 kV (Phase C)	601.2 kV (T1), 603.1 kV (T2), 656.6 kV (T3), 705 kV (T4)	610.2 kV	649.9 kV	603.4 kV	42.6 kV	46 kV	45.9 kV	2 kV	2.2 kV	2.2 kV	0.6 kV	0.7 kV	0.7 kV
	4	None	585.4 kV (T1), 595.9 kV (T2), 671.5 kV (T2), 719.3 kV (T4)	626.2 kV	659.8 kV	553.2 kV	41.6 kV	45 kV	44.7 kV	2.3 kV	2.5 kV	2.5 kV	0.6 kV	0.7 kV	0.7 kV
		400 kV (All Phases)	583.7 kV (T1), 591.7 kV (T2), 662.3 kV (T3), 708.1 kV (T4)	619.1 kV	650.2 kV	547.6 kV	41.2 kV	44.5 kV	44.3 kV	2.3 kV	2.5 kV	2.5 kV	0.6 kV	0.7 kV	0.7 kV
		400 kV (Phase C)	585.4 kV (T1), 595.8 kV (T2), 671.3 kV (T3), 719.3 kV (T4)	626.1 kV	659.8 kV	552.9 kV	41.6 kV	45 kV	44.7 kV	2.3 kV	2.5 kV	2.5 kV	0.6 kV	0.7 kV	0.7 kV

Figure 4.17: Results for 20 kA 1.2/50 μs direct stroke to the Phase C conductor without a surge capacitance.

4.3.8 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase C Conductor With a Surge Capacitance

In this part, lightning source has been adjusted as 20 kA 1.2/50 μs and the Phase C conductor of the tower was exposed to lightning stroke. A surge capacitance of 0.36 μF is used in the network. The results are demonstrated in Figure 4.18 on the next page.

For the results of different cases and scenarios in Figure 4.18, following discussions and comments can be made:

- For all scenarios, the values in 400 kV level are almost the same as the case without a surge capacitance; whereas, the values in 15.75 kV and 6 kV level are significantly less than the case without a surge capacitance.
- When the lightning strikes to Phase C conductor without the operation of any surge arresters (Case 1), all phases of each level are below BIL.
- As the number of towers increase, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases generally; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage on each level reduces. All phases of each level are below BIL.
- When one surge arrester in Phase C of 400 kV level is operating (Case 7), the results are slightly higher than Case 2 for Phase A and Phase B of 400 kV level and all phases of 15.75 kV level; whereas, Phase C of 400 kV level is almost same. Induced voltage on each level is below BIL.
- As a result, although the system is safe without operation of any surge arrester, one surge arrester operation in Phase C of 400 kV level (Case 7) can be used to make induced voltages less in 15.75 kV side.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 15.75 kV Side			Induced Voltage Peak on 6 kV Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	1.5 MV (T1)	1.5 MV	1.51 MV	1.62 MV	54 kV	62.6 kV	62.7 kV	2.3 kV	2.8 kV	2.9 kV	1.1 kV	1.3 kV	1.4 kV
		400 kV (All Phases)	643.8 kV (T2)	643.1 kV	678.1 kV	877.1 kV	25 kV	28.9 kV	29.2 kV	1.9 kV	2.2 kV	2.3 kV	1.1 kV	1.3 kV	1.4 kV
		400 kV (Phase C)	751 kV (T1)	752.4 kV	758.7 kV	877.1 kV	27 kV	31.3 kV	31.3 kV	1.9 kV	2.2 kV	2.3 kV	1.1 kV	1.3 kV	1.4 kV
2	1	None	961.5 kV (T1), 984.3 kV (T2)	968 kV	971.4 kV	1.05 MV	34.4 kV	39.8 kV	39.8 kV	2.2 kV	2.6 kV	2.7 kV	1.1 kV	1.3 kV	1.4 kV
		400 kV (All Phases)	673.6 kV (T1), 682.4 kV (T2)	668 kV	680.8 kV	856 kV	24.8 kV	28.7 kV	28.8 kV	1.8 kV	2.1 kV	2.2 kV	1.1 kV	1.3 kV	1.4 kV
		400 kV (Phase C)	748.7 kV (T1), 763.7 kV (T2)	747.1 kV	748.1 kV	856 kV	26.5 kV	30.7 kV	30.6 kV	1.8 kV	2.1 kV	2.2 kV	1.1 kV	1.3 kV	1.4 kV
	2	None	1.01 MV (T1), 1.05 MV (T2)	991.5 kV	973.1 kV	1.02 MV	34.8 kV	40.3 kV	40.3 kV	1.7 kV	2 kV	2 kV	0.6 kV	0.7 kV	0.7 kV
		400 kV (All Phases)	735.9 kV (T1), 795 kV (T2)	689.6 kV	707 kV	792.4 kV	25.3 kV	29.3 kV	29.4 kV	1.7 kV	2 kV	2 kV	0.6 kV	0.7 kV	0.7 kV
		400 kV (Phase C)	774 kV (T1), 833 kV (T2)	765 kV	762.6 kV	793.5 kV	27 kV	31.2 kV	31.2 kV	1.7 kV	2 kV	2 kV	0.6 kV	0.7 kV	0.7 kV
3	1	None	722.4 kV (T1), 717.4 kV (T2), 755.2 kV (T3)	727.3 kV	701.7 kV	1.04 MV	25.4 kV	29.3 kV	29.4 kV	2.2 kV	2.6 kV	2.7 kV	1.1 kV	1.3 kV	1.4 kV
		400 kV (All Phases)	648.5 kV (T1), 654.6 kV (T2), 664.8 kV (T3)	645.7 kV	632.5 kV	855.6 kV	22.7 kV	26.2 kV	26.4 kV	1.8 kV	2.1 kV	2.2 kV	1.1 kV	1.3 kV	1.4 kV
		400 kV (Phase C)	669.6 kV (T1), 667.9 kV (T2), 677.7 kV (T3)	669.4 kV	650.4 kV	855.6 kV	23.1 kV	26.7 kV	26.7 kV	1.8 kV	2.1 kV	2.2 kV	1.1 kV	1.3 kV	1.4 kV
	2	None	726 kV (T1), 771.9 kV (T2), 765.2 kV (T3)	727.6 kV	716.2 kV	770.3 kV	25.6 kV	29.6 kV	29.5 kV	1.4 kV	1.6 kV	1.7 kV	0.5 kV	0.6 kV	0.6 kV
		400 kV (All Phases)	663.8 kV (T1), 714.7 kV (T2), 721.4 kV (T3)	651.1 kV	655.9 kV	698 kV	23.6 kV	27.3 kV	27.4 kV	1.4 kV	1.6 kV	1.7 kV	0.5 kV	0.6 kV	0.6 kV
		400 kV (Phase C)	684.3 kV (T1), 735.6 kV (T2), 732 kV (T3)	687.1 kV	679.3 kV	699.1 kV	24.3 kV	28.1 kV	28.1 kV	1.4 kV	1.6 kV	1.7 kV	0.5 kV	0.6 kV	0.6 kV
	3	None	754.4 kV (T1), 731.1 kV (T2), 850.3 kV (T3)	752 kV	759 kV	738 kV	26.7 kV	308 kV	30.8 kV	1.4 kV	1.7 kV	1.7 kV	0.4 kV	0.5 kV	0.5 kV
		400 kV (All Phases)	678 kV (T1), 674.6 kV (T2), 779.1 kV (T3)	665.2 kV	697.3 kV	684.1 kV	24 kV	27.8 kV	27.8 kV	1.4 kV	1.7 kV	1.7 kV	0.4 kV	0.5 kV	0.5 kV
		400 kV (Phase C)	730.2 kV (T1), 707.4 kV (T2), 829.5 kV (T3)	725 kV	751.5 kV	693.6 kV	25.4 kV	29.4 kV	29.3 kV	1.4 kV	1.7 kV	1.7 kV	0.4 kV	0.5 kV	0.5 kV
4	1	None	613.2 kV (T1), 574 kV (T2), 599.3 kV (T3), 644.9 kV (T4)	600.6 kV	548.4 kV	1.04 MV	21.1 kV	24.8 kV	25.8 kV	2.2 kV	2.6 kV	2.7 kV	1.1 kV	1.3 kV	1.4 kV
		400 kV (All Phases)	548.2 kV (T1), 546.9 kV (T2), 539.3 kV (T3), 547.9 kV (T4)	544.9 kV	511.7 kV	855.6 kV	19.3 kV	22.3 kV	22.4 kV	1.8 kV	2.1 kV	2.2 kV	1.1 kV	1.3 kV	1.4 kV
		400 kV (Phase C)	548.5 kV (T1), 547.1 kV (T2), 539.7 kV (T3), 548.3 kV (T4)	545.4 kV	511.9 kV	855.6 kV	19.3 kV	22.3 kV	22.4 kV	1.8 kV	2.1 kV	2.2 kV	1.1 kV	1.3 kV	1.4 kV
	2	None	591.7 kV (T1), 643.3 kV (T2), 650.1 kV (T3), 598.5 kV (T4)	572.8 kV	550.5 kV	662.8 kV	20.3 kV	23.5 kV	23.6 kV	1.4 kV	1.6 kV	1.6 kV	0.5 kV	0.6 kV	0.6 kV
		400 kV (All Phases)	588.1 kV (T1), 639.2 kV (T2), 644.4 kV (T3), 596.3 kV (T4)	570.1 kV	546.9 kV	652.5 kV	20.1 kV	23.3 kV	23.4 kV	1.4 kV	1.6 kV	1.6 kV	0.5 kV	0.6 kV	0.6 kV
		400 kV (Phase C)	588.7 kV (T1), 639.6 kV (T2), 644.6 kV (T3), 596.8 kV (T4)	570.3 kV	546.9 kV	652.5 kV	20.1 kV	23.3 kV	23.4 kV	1.4 kV	1.6 kV	1.6 kV	0.5 kV	0.6 kV	0.6 kV
	3	None	601.2 kV (T1), 603.6 kV (T2), 657.2 kV (T3), 795.8 kV (T4)	608.6 kV	649.5 kV	605.1 kV	22.1 kV	25.7 kV	26 kV	1 kV	1.2 kV	1.2 kV	0.3 kV	0.4 kV	0.4 kV
		400 kV (All Phases)	599.3 kV (T1), 596.2 kV (T2), 649.6 kV (T3), 696.2 kV (T4)	605.2 kV	639 kV	600.4 kV	21.9 kV	25.4 kV	25.3 kV	1 kV	1.2 kV	1.2 kV	0.3 kV	0.4 kV	0.4 kV
		400 kV (Phase C)	601.2 kV (T1), 603.1 kV (T2), 656.6 kV (T3), 705 kV (T4)	608.4 kV	648.9 kV	603.3 kV	21.9 kV	25.4 kV	25.3 kV	1 kV	1.2 kV	1.2 kV	0.3 kV	0.4 kV	0.4 kV
	4	None	585.4 kV (T1), 595.9 kV (T2), 671.5 kV (T2), 719.3 kV (T4)	623 kV	656.9 kV	552.8 kV	21.6 kV	25 kV	24.8 kV	1.2 kV	1.4 kV	1.4 kV	0.3 kV	0.4 kV	0.4 kV
		400 kV (All Phases)	583.7 kV (T1), 591.7 kV (T2), 662.3 kV (T3), 708.1 kV (T4)	616.7 kV	648.3 kV	547.6 kV	21.6 kV	25 kV	24.8 kV	1.2 kV	1.4 kV	1.4 kV	0.3 kV	0.4 kV	0.4 kV
		400 kV (Phase C)	585.4 kV (T1), 595.8 kV (T2), 671.3 kV (T3), 719.3 kV (T4)	623 kV	656.9 kV	547.6 kV	21.6 kV	25 kV	24.8 kV	1.2 kV	1.4 kV	1.4 kV	0.3 kV	0.4 kV	0.4 kV

Figure 4.18: Results for 20 kA 1.2/50 μs direct stroke to the Phase C conductor with a surge capacitance.

4.4 Simulation Results of the Second NPP Model

In this part, the results of each simulation for the second NPP will be investigated in detail. To simplify, different combinations of surge arresters have been defined as "Cases". Also, "Scenarios" have been used for the different system models in terms of tower number and stroke location on the towers.

The cases could be assigned as follows:

- **Case 1**: None of the surge arresters are operating (Written as “None” in the figures).
- **Case 2**: One surge arrester in each phase of 400 kV level is operating (Written as “400 kV (All Phases)” in the figures).
- **Case 3**: One surge arrester in Phase A of 400 kV level is operating (Written as “400 kV (Phase A)” in the figures).
- **Case 4**: One surge arrester in each phase of 400 kV and 20 kV levels is operating (Written as “400 kV + 20 kV” in the figures).
- **Case 5**: One surge arrester in each phase of in 400 kV, 20 kV, and 6.9 kV levels is operating (Written as “400 kV + 20 kV + 6.9 kV” in the figures).
- **Case 6**: One surge arrester in Phase B of 400 kV level is operating (Written as “400 kV (Phase B)” in the figures).
- **Case 7**: One surge arrester in Phase C of 400 kV level is operating (Written as “400 kV (Phase C)” in the figures)

Simulation results will be given in 4 main parts in terms of the stroke type. In each main part, firstly, the simulation results without a surge capacitance will be given and discussions will be made on the results. Then, the results with a surge capacitance will be given, the discussion will be made, and results will be compared with the case without a surge capacitance.

In figures, it should be noted that black colour for the induced voltage values show the safe values under BIL; whereas, the red colour for the induced voltage values show the values above BIL. BILs for the equipment are given as

- 29 kV for 6.9 kV level
- 150 kV for 20 kV level
- 1300 kV for 400 kV level.

Also, it is worth to state that Tower 1 in the results is the rightmost tower which is closest to the primary transformer, and Tower 4 is the leftmost tower which is the furthest from the primary transformer.

4.4.1 Results for 200 kA 1.2/50 μs Direct Stroke to the Ground Wire Without a Surge Capacitance

In this part, the lightning source has been adjusted as 200 kA 1.2/50 μs and the ground wire of the tower was exposed to the lightning stroke. No surge capacitance is used in the network. The simulation results will be given in Figure 4.19 on the next page.

For the results of different cases and scenarios in 4.19, following discussions and comments can be made:

- When the lightning strikes to the ground wire of the towers without the operation of any surge arresters (Case 1), all phases of 400 kV, 20 kV and 6.9 kV levels are above BIL for all scenarios.
- As the number of towers increases, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), Phase A of 400 kV level is above BIL for all scenarios. The other phases of 400 kV level is below BIL for all scenarios.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltages 20 kV and 6.9 kV levels are below BIL for all scenarios.
- When one surge arrester in Phase A of 400 kV level is operating (Case 3), although Phase A of 400 kV level stays almost constant, the induced voltages increase in the other phases of 400 kV level significantly compared to Case 2. Phase B and Phase C of 400 kV level values become more than BIL. Also, induced voltage in all phases of 20 kV level increases significantly. Phase B of 20 kV level is above BIL except for 1 existing tower scenario. Phase C of 20 kV level is above BIL for 3 and 4 existing towers scenarios and 2 existing towers scenario if the lightning comes to Tower 2. Phase A of 20 kV level is below BIL except for 4 existing towers scenario when the stroke comes to Tower 3 or Tower 4. Moreover, there is a slight increase in 6.9 kV level but the values are almost same as the values in Case 2.
- When one surge arrester in each phase of 400 kV and 20 kV levels is operating (Case 4), the magnitudes of the induced voltages in 400 kV level are similar as the operation of only 400 kV level surge arresters (Case 2). For 20 kV level, the induced voltage values reduce compared to Case 2. Moreover, there is a slight decrease in 6.9 kV level but the values are almost same as the values in Case 2. Since 20 kV level is already below BIL without operation of the surge arresters in 20 kV level (Case 2), using 20 kV level surge arresters is not necessary.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 20 kV Side			Induced Voltage Peak on 6.9 kV Side			Induced Voltage Peak on 690 V Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	32.7 MV (T1)	25.7 MV	17.5 MV	9.7 MV	1.35 MV	1.64 MV	1.53 MV	39.8 kV	44.5 kV	41.4 kV	5.6 kV	5.7 kV	5.6 kV	3.6 kV	3.6 kV	3.5 kV
		400 kV (All Phases)	17.8 MV (T1)	2 MV	734.2 kV	351.6 kV	72.8 kV	79.3 kV	75.2 kV	12 kV	12.1 kV	11.8 kV	5.5 kV	5.1 kV	5.1 kV	3.5 kV	3.1 kV	3 kV
		400 kV (Phase A)	17.8 MV (T1)	2.01 MV	771.4 kV	368.1 kV	72.9 kV	79.4 kV	75.3 kV	12 kV	12.1 kV	11.8 kV	5.5 kV	5.1 kV	5.1 kV	3.5 kV	3.1 kV	3 kV
		400 kV + 20 kV	17.8 MV (T1)	2 MV	734.2 kV	351.6 kV	58.1 kV	59.9 kV	57.2 kV	11.9 kV	11.9 kV	11.7 kV	5.5 kV	5.1 kV	5.1 kV	3.5 kV	3.1 kV	3 kV
		400 kV + 20 kV + 6.9 kV	17.8 MV (T1)	2 MV	734.2 kV	351.6 kV	58.1 kV	59.9 kV	57.2 kV	11.9 kV	11.9 kV	11.7 kV	5.5 kV	5.1 kV	5.1 kV	3.5 kV	3.1 kV	3 kV
2	1	None	23.6 MV (T1), 24.9 MV (T2)	19.3 MV	13.3 MV	7.3 MV	1.02 MV	1.24 MV	1.16 MV	36.3 kV	39.3 kV	37.4 kV	5.5 kV	5.6 kV	5.4 kV	3.5 kV	3.5 kV	3.5 kV
		400 kV (All Phases)	14.4 MV (T1), 11.7 MV (T2)	1.91 MV	978.6 kV	763.9 kV	80 kV	98.2 kV	93.1 kV	11.9 kV	12.1 kV	11.8 kV	5.4 kV	5 kV	5 kV	3.4 kV	3 kV	3 kV
		400 kV (Phase A)	14.4 MV (T1), 11.8 MV (T2)	1.91 MV	2.15 MV	1.35 MV	119.1 kV	161.4 kV	147.9 kV	11.9 kV	12.1 kV	11.8 kV	5.4 kV	5 kV	5 kV	3.4 kV	3 kV	3 kV
		400 kV + 20 kV	14.4 MV (T1), 11.7 MV (T2)	1.91 MV	978.6 kV	763.9 kV	57.5 kV	60.3 kV	57.4 kV	11.8 kV	11.9 kV	11.6 kV	5.4 kV	5 kV	5 kV	3.4 kV	3 kV	3 kV
		400 kV + 20 kV + 6.9 kV	14.4 MV (T1), 11.7 MV (T2)	1.91 MV	978.6 kV	763.9 kV	57.5 kV	60.3 kV	57.4 kV	11.8 kV	11.9 kV	11.6 kV	5.4 kV	5 kV	5 kV	3.4 kV	3 kV	3 kV
	2	None	24.4 MV (T1), 26.7 MV (T2)	19.3 MV	13.2 MV	7.3 MV	1 MV	1.23 MV	1.15 MV	47.5 kV	56.3 kV	52.6 kV	4.6 kV	5.5 kV	5.1 kV	2.6 kV	3 kV	2.8 kV
		400 kV (All Phases)	11.2 MV (T1), 18.7 MV (T2)	1.71 MV	1.15 MV	862.5 kV	90.8 kV	110.5 kV	103.7 kV	12 kV	14.2 kV	13.3 kV	1.7 kV	2.2 kV	2 kV	1.6 kV	2 kV	1.8 kV
		400 kV (Phase A)	11.1 MV (T1), 18.7 MV (T2)	1.74 MV	2.63 MV	1.63 MV	140.6 kV	192.6 kV	175.8 kV	12.2 kV	14.5 kV	13.5 kV	2.2 kV	2.6 kV	2.4 kV	1.6 kV	2.2 kV	2 kV
		400 kV + 20 kV	11.2 MV (T1), 18.7 MV (T2)	1.71 MV	1.15 MV	862.5 kV	55.4 kV	60.9 kV	57.7 kV	8.9 kV	9.9 kV	9.3 kV	1.7 kV	2.2 kV	2 kV	1.6 kV	2 kV	1.8 kV
		400 kV + 20 kV + 6.9 kV	11.2 MV (T1), 18.7 MV (T2)	1.71 MV	1.15 MV	862.5 kV	55.4 kV	60.9 kV	57.7 kV	8.9 kV	9.9 kV	9.3 kV	1.7 kV	2.2 kV	2 kV	1.6 kV	2 kV	1.8 kV
3	1	None	18.4 MV (T1), 18.8 MV (T2), 19.8 MV (T3)	15 MV	10.7 MV	6 MV	804.3 kV	987 kV	921.3 kV	35.9 kV	38.9 kV	37 kV	5.5 kV	5.6 kV	5.4 kV	3.5 kV	3.5 kV	3.5 kV
		400 kV (All Phases)	14.3 MV (T1), 9.8 MV (T2), 9.6 MV (T3)	1.9 MV	919 kV	788.1 kV	73.6 kV	90.3 kV	86.2 kV	11.9 kV	12.1 kV	11.8 kV	5.5 kV	5.1 kV	5.2 kV	3.4 kV	3.4 kV	3.4 kV
		400 kV (Phase A)	14.3 MV (T1), 9.8 MV (T2), 9.6 MV (T3)	1.9 MV	2.42 MV	1.64 MV	124.9 kV	174.4 kV	159.4 kV	11.9 kV	12.1 kV	11.8 kV	5.5 kV	5.1 kV	5.2 kV	3.4 kV	3.4 kV	3.4 kV
		400 kV + 20 kV	14.3 MV (T1), 9.8 MV (T2), 9.6 MV (T3)	1.9 MV	919 kV	788.1 kV	57.3 kV	60.1 kV	57.3 kV	11.8 kV	11.9 kV	11.6 kV	5.5 kV	5.1 kV	5.2 kV	3.4 kV	3.4 kV	3.4 kV
		400 kV + 20 kV + 6.9 kV	14.3 MV (T1), 9.8 MV (T2), 9.6 MV (T3)	1.9 MV	919 kV	788.1 kV	57.3 kV	60.1 kV	57.3 kV	11.8 kV	11.9 kV	11.6 kV	5.5 kV	5.1 kV	5.2 kV	3.4 kV	3.4 kV	3.4 kV
	2	None	18.5 MV (T1), 19.3 MV (T2), 20 MV (T3)	15.1 MV	10.5 MV	5.83 MV	803.4 kV	981 kV	916.6 kV	35.3 kV	40.5 kV	38.1 kV	4.1 kV	4.6 kV	4.3 kV	3.5 kV	3.5 kV	3.5 kV
		400 kV (All Phases)	9 MV (T1), 16.5 MV (T2), 13.5 MV (T3)	1.57 MV	1.09 MV	873.4 kV	84.3 kV	102.9 kV	96.4 kV	11.5 kV	13.5 kV	12.6 kV	1.6 kV	2.1 kV	1.9 kV	1.4 kV	1.3 kV	1.3 kV
		400 kV (Phase A)	9.2 MV (T1), 16.5 MBV (T2), 13.5 MV (T3)	1.6 MV	2.86 MV	1.97 MV	144.3 kV	203.1 kV	185.6 kV	11.5 kV	13.7 kV	12.7 kV	1.6 kV	2.1 kV	1.9 kV	1.4 kV	1.3 kV	1.3 kV
		400 kV + 20 kV	10 MV (T1), 16.5 MV (T2), 13.5 MV (T3)	1.57 MV	1.09 MV	873.4 kV	54.1 kV	59.7 kV	56.6 kV	8.8 kV	9.8 kV	9.2 kV	1.6 kV	2.1 kV	1.9 kV	1.4 kV	1.3 kV	1.3 kV
		400 kV + 20 kV + 6.9 kV	11 MV (T1), 16.5 MV (T2), 13.5 MV (T3)	1.57 MV	1.09 MV	873.4 kV	54.1 kV	59.7 kV	56.6 kV	8.8 kV	9.8 kV	9.2 kV	1.6 kV	2.1 kV	1.9 kV	1.4 kV	1.3 kV	1.3 kV
	3	None	19.1 MV (T1), 19.7 MV (T2), 20.8 MV (T3)	15.8 MV	10.6 MV	5.91 MV	820.9 kV	1 MV	934.4 kV	46.7 kV	56 kV	52.3 kV	4.1 kV	4.9 kV	4.6 kV	3.5 kV	3.5 kV	3.5 kV
		400 kV (All Phases)	8.5 MV (T1), 12.7 MV (T2), 19.1 MV (T3)	1.55 MV	1.19 MV	908.9 kV	91.5 kV	113.7 kV	107.3 kV	11 kV	13.7 kV	12.8 kV	1.6 kV	1.8 kV	1.7 kV	1.4 kV	1.6 kV	1.2 kV
		400 kV (Phase A)	8.6 MV (T1), 12.7 MV (T2), 19.1 MV (T3)	1.56 MV	3.54 MV	2.45 MV	180 kV	251.9 kV	230 kV	12.1 kV	15.4 kV	14.2 kV	1.6 kV	1.8 kV	1.7 kV	1.4 kV	1.6 kV	1.2 kV
		400 kV + 20 kV	8.5 MV (T1), 12.7 MV (T2), 19.1 MV (T3)	1.55 MV	1.19 MV	908.9 kV	57.5 kV	65.1 kV	61.6 kV	6.8 kV	7.8 kV	7.4 kV	1.6 kV	1.8 kV	1.7 kV	1.4 kV	1.6 kV	1.2 kV
		400 kV + 20 kV + 6.9 kV	8.5 MV (T1), 12.7 MV (T2), 19.1 MV (T3)	1.55 MV	1.19 MV	908.9 kV	57.5 kV	65.1 kV	61.6 kV	6.8 kV	7.8 kV	7.4 kV	1.6 kV	1.8 kV	1.7 kV	1.4 kV	1.6 kV	1.2 kV
4	1	None	17.3 MV (T1), 15.4 MV (T2), 16.9 MV (T3), 16.6 MV (T4)	12.4 MV	9.1 MV	5.2 MV	680.5 kV	837.3 kV	781.7 kV	35.9 kV	38.9 kV	37 kV	5.5 kV	5.6 kV	5.4 kV	3.5 kV	3.5 kV	3.5 kV
		400 kV (All Phases)	14.3 MV (T1), 8.5 MV (T2), 8.4 MV (T3), 8 MV (T4)	1.9 MV	903.9 kV	777 kV	71.4 kV	85 kV	80.8 kV	11.9 kV	12.1 kV	11.8 kV	5.4 kV	5 kV	5.1 kV	3.4 kV	3.4 kV	3.4 kV
		400 kV (Phase A)	14.3 MV (T1), 8.5 MV (T2), 8.4 MV (T3), 8 MV (T4)	1.9 MV	2.2 MV	1.5 MV	116.1 kV	160.9 kV	147.4 kV	11.9 kV	12.1 kV	11.8 kV	5.4 kV	5 kV	5.1 kV	3.4 kV	3.4 kV	3.4 kV
		400 kV + 20 kV	14.3 MV (T1), 8.5 MV (T2), 8.4 MV (T3), 8 MV (T4)	1.9 MV	903.9 kV	778 kV	57.3 kV	60.1 kV	57.2 kV	11.8 kV	11.9 kV	11.6 kV	5.4 kV	5 kV	5.1 kV	3.4 kV	3.4 kV	3.4 kV
		400 kV + 20 kV + 6.9 kV	14.3 MV (T1), 8.5 MV (T2), 8.4 MV (T3), 8 MV (T4)	1.9 MV	903.9 kV	779 kV	57.3 kV	60.1 kV	57.2 kV	11.8 kV	11.9 kV	11.6 kV	5.4 kV	5 kV	5.1 kV	3.4 kV	3.4 kV	3.4 kV
	2	None	15.4 MV (T1), 16.5 MV (T2), 17 MV (T3), 16.2 MV (T4)	12.3 MV	8.7 MV	4.9 MV	659.4 kV	807.4 kV	753.6 kV	34.6 kV	39.7 kV	37.3 kV	4 kV	4.5 kV	4.3 kV	2 kV	2.2 kV	2.1 kV
		400 kV (All Phases)	8.5 MV (T1), 16.3 MV (T2), 10.7 MV (T3), 11.4 MV (T4)	1.56 MV	1.08 MV	822.5 kV	83.3 kV	101.7 kV	95.2 kV	11.5 kV	13.6 kV	12.7 kV	1.6 kV	2.1 kV	1.9 kV	1.2 kV	1.1 kV	2 kV
		400 kV (Phase A)	8.5 MV (T1), 16.3 MV (T2), 10.7 MV (T3), 11.4 MV (T4)	1.58 MV	2.5 MV	1.74 MV	129.5 kV	180.7 kV	165.5 kV	11.5 kV	13.6 kV	12.7 kV	1.6 kV	2.1 kV	1.9 kV	1.2 kV	1.1 kV	1 kV
		400 kV + 20 kV	8.5 MV (T1), 16.3 MV (T2), 10.7 MV (T3), 11.4 MV (T4)	1.56 MV	1.07 MV	822.5 kV	54 kV	59.6 kV	56.5 kV	8.8 kV	9.8 kV	9.2 kV	1.6 kV	2.1 kV	1.9 kV	1.2 kV	1.1 kV	3 kV
		400 kV + 20 kV + 6.9 kV	8.5 MV (T1), 16.3 MV (T2), 10.7 MV (T3), 11.4 MV (T4)	1.56 MV	1.07 MV	822.5 kV	55 kV	59.6 kV	56.5 kV	8.8 kV	9.8 kV	9.2 kV	1.6 kV	2.1 kV	1.9 kV	1.2 kV	1.1 kV	4 kV
	3	None	17.1 MV (T1), 17 MV (T2), 16.8 MV (T3), 18.1 MV (T4)	14.3 MV	9.8 MV	5.4 MV	753.4 kV	919.2 kV	858.4 kV	33.1 kV	40 kV	37.3 kV	3.3 kV	3.8 kV	3.6 kV	1.8 kV	2.1 kV	1.9 kV
		400 kV (All Phases)	7.7 MV (T1), 10.7 MV (T2), 16.8 MV (T3), 15.2 MV (T4)	1.47 MV	1.12 MV	920.9 kV	84.9 kV	105.9 kV	81.7 kV	11.1 kV	14.2 kV	13 kV	1.5 kV	1.7 kV	1.6 kV	1.2 kV	1.5 kV	1.3 kV
		400 kV (Phase A)	7.8 MV (T1), 10.7 MV (T2), 16.8 MV (T3), 15.2 MV (T4)	1.48 MV	3.28 MV	2.28 MV	166.2 kV	234 kV	213.9 kV	11.1 kV	14.2 kV	13 kV	1.5 kV	1.7 kV	1.6 kV	1.2 kV	1.5 kV	1.3 kV
		400 kV + 20 kV	7.7 MV (T1), 10.7 MV (T2), 16.8 MV (T3), 15.2 MV (T4)	1.47 MV	1.12 MV	917.5 kV	56.1 kV	63.8 kV	60.3 kV	6.5 kV	7.4 kV	7 kV	1.5 kV	1.7 kV	1.6 kV	1.2 kV	1.5 kV	1.3 kV
		400 kV + 20 kV + 6.9 kV	7.7 MV (T1), 10.7 MV (T2), 16.8 MV (T3), 15.2 MV (T4)	1.47 MV	1.12 MV	917.5 kV	56.1 kV	63.8 kV	60.3 kV	6.5 kV	7.4 kV	8 kV	1.5 kV	1.7 kV	1.6 kV	1.2 kV	1.5 kV	1.3 kV
	4	None	16.1 MV (T1), 16.2 MV (T2), 17.6 MV (T3), 19.1 MV (T4)	14.4 MV	10.1 MV	5.5 MV	761.1 kV	931.1 kV	868.7 kV	43 kV	52.1 kV	48.6 kV	3.5 kV	4.2 kV	3.9 kV	1.3 kV	1.5 kV	1.4 kV
		400 kV (All Phases)	7 MV (T1), 10.4 MV (T2), 14.3 MV (T3), 19.1 MV (T4)	1.48 MV	1.14 MV	968.8 kV	88.7 kV	111.1 kV	105.4 kV	11.6 kV	15.4 kV	15 kV	1.5 kV	1.8 kV	1.7 kV	1.2 kV	1.5 kV	1.3 kV
		400 kV (Phase A)	7.2 MV (T1), 10.6 MV (T2), 14.3 MV (T3), 19 MV (T4)	1.49 MV	3.84 MV	2.76 MV	192.6 kV	271.1 kV	248 kV	11.6 kV	15.4 kV	14 kV	1.5 kV	1.8 kV	1.7 kV	1.2 kV	1.5 kV	1.3 kV
		400 kV + 20 kV	7 MV (T1), 10.4 MV (T2), 14.3 MV (T3), 19.1 MV (T4)	1.47 MV	1.14 MV	961.9 kV	57.6 kV	66.2 kV	63 kV	7.6 kV	9 kV	8.4 kV	1.5 kV	1.8 kV	1.7 kV	1.2 kV	1.5 kV	1.3 kV
		400 kV + 20 kV + 6.9 kV	7 MV (T1), 10.4 MV (T2), 14.3 MV (T3), 19.1 MV (T4)	1.47 MV	1.14 MV	961.9 kV	57.6 kV	66.2 kV	63 kV	7.6 kV	9 kV	8.4 kV	1.5 kV	1.8 kV	1.7 kV	1.2 kV	1.5 kV	1.3 kV

Figure 4.19: Results for 200 kA 1.2/50 μs direct stroke to the ground wire without a surge capacitance.

- When one surge arrester in each phase of 400 kV, 20 kV, and 6.9 kV levels is operating (Case 5), all results are the same as protection with only 400 kV and 20 kV surge arresters (Case 4) except for 6.9 kV level. The magnitudes of the induced voltages in 6.9 kV level slightly reduce for some scenarios; however, for most of the scenarios this level stays constant. Hence, there is no need to operate 6.9 kV level surge arresters as they don't have significant effect.
- In this simulation, Case 2 seems as the most reasonable case among the other cases. Although Phase A of 400 kV level is above BIL, the other phases of that level the other levels are below BIL. In order to make Phase A of 400 kV level below BIL, a surge arrester with different ratings might be preferred.

4.4.2 Results for 200 kA 1.2/50 μs Direct Stroke to the Ground Wire With a Surge Capacitance

In this part, the lightning source has been adjusted as 200 kA 1.2/50 μs and the ground wire of the tower was exposed to lightning stroke. A surge capacitance of 0.36 μF is used in the network. The simulation results will be given in Figure 4.20 on the next page.

For the results of different cases and scenarios in Figure 4.20, following discussions and comments can be made:

- For all scenarios, the values in 400 kV level are almost the same as the case without a surge capacitance; whereas, the values in 20 kV and 6.9 kV levels are significantly less than the case without a surge capacitance.
- When lightning strikes to the ground wire of the towers without the operation of any surge arresters (Case 1), all phases of 400 kV and 20 kV levels are above BIL for all scenarios. In 6.9 kV level, Phase A is below BIL for all scenarios; however, Phase B and Phase C are above BIL for few scenarios.
- As the number of towers increases, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), Phase A of 400 kV level is above BIL for all scenarios. The other phases of 400 kV level is below BIL for all scenarios.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltages in 20 kV and 6.9 kV levels are below BIL for all scenarios.
- When one surge arrester in Phase A of 400 kV level is operating (Case 3), although Phase A of 400 kV level stays almost constant, the induced voltage increases in the other phases of 400 kV level significantly compared to Case 2.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 20 kV Side			Induced Voltage Peak on 6.9 kV Side			Induced Voltage Peak on 690 V Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	32.6 MV (T1)	25.6 MV	17.5 MV	9.7 MV	769 kV	1.12 MV	997.2 kV	22.5 kV	30 kV	26.6 kV	3.2 kV	3.5 kV	3.3 kV	2 kV	2.2 kV	2.1 kV
		400 kV (All Phases)	17.8 MV (T1)	2.01 MV	732.5 kV	355.5 kV	41.5 kV	50.6 kV	46 kV	6.8 kV	7.4 kV	7 kV	3.1 kV	2.9 kV	2.9 kV	2 kV	2.2 kV	2.1 kV
		400 kV (Phase A)	17.8 MV (T1)	2.01 MV	767.6 kV	371.9 kV	41.5 kV	50.7 kV	46 kV	6.8 kV	7.4 kV	7 kV	3.1 kV	2.9 kV	2.9 kV	2 kV	2.2 kV	2.1 kV
		400 kV + 20 kV	17.8 MV (T1)	2.01 MV	732.1 kV	355.1 kV	40.9 kV	49.5 kV	45.1 kV	6.8 kV	7.4 kV	7 kV	3.1 kV	2.9 kV	2.9 kV	2 kV	2.2 kV	2.1 kV
		400 kV + 20 kV + 6.9 kV	17.8 MV (T1)	2.01 MV	732.1 kV	355.1 kV	40.9 kV	49.5 kV	45.1 kV	6.8 kV	7.4 kV	7 kV	3.1 kV	2.9 kV	2.9 kV	2 kV	2.2 kV	2.1 kV
2	1	None	23.6 MV (T1), 24.9 MV (T2)	19.3 MV	13.3 MV	7.3 MV	577.5 kV	845.3 kV	755.3 kV	20.5 kV	24.9 kV	22.7 kV	3.1 kV	3.4 kV	3.2 kV	2 kV	2.1 kV	2 kV
		400 kV (All Phases)	14.4 MV (T1), 11.7 MV (T2)	1.91 MV	977.6 kV	762.8 kV	45.8 kV	67.1 kV	61.4 kV	6.8 kV	7.3 kV	6.9 kV	3 kV	3.3 kV	3.1 kV	2 kV	2.1 kV	2 kV
		400 kV (Phase A)	14.4 MV (T1), 11.8 MV (T2)	1.91 MV	2.15 MV	1.35 MV	68 kV	115 kV	100.5 kV	6.8 kV	7.3 kV	6.9 kV	3 kV	3.3 kV	3.1 kV	2 kV	2.1 kV	2 kV
		400 kV + 20 kV	14.4 MV (T1), 11.7 MV (T2)	1.91 MV	976.7 kV	761 kV	40 kV	55.1 kV	51.8 kV	6.8 kV	7.3 kV	6.9 kV	3 kV	3.3 kV	3.1 kV	2 kV	2.1 kV	2 kV
		400 kV + 20 kV + 6.9 kV	14.4 MV (T1), 11.7 MV (T2)	1.91 MV	976.7 kV	761 kV	40 kV	55.1 kV	51.8 kV	6.8 kV	7.3 kV	6.9 kV	3 kV	3.3 kV	3.1 kV	2 kV	2.1 kV	2 kV
	2	None	24.4 MV (T1), 26.7 MV (T2)	19.3 MV	13.2 MV	7.3 MV	573.6 kV	832.8 kV	747.1 kV	27 kV	37.6 kV	33.5 kV	2.6 kV	3.7 kV	3.2 kV	1.5 kV	2 kV	1.8 kV
		400 kV (All Phases)	11.2 MV (T1), 18.7 MV (T2)	1.71 MV	1.15 MV	865.5 kV	51.9 kV	75.2 kV	67.6 kV	6.8 kV	9.5 kV	8.5 kV	1 kV	1.5 kV	1.3 kV	0.7 kV	0.8 kV	0.8 kV
		400 kV (Phase A)	11.1 MV (T1), 18.7 MV (T2)	1.74 MV	2.63 MV	1.63 MV	80.3 kV	137.7 kV	119.8 kV	7 kV	9.8 kV	8.6 kV	1.2 kV	1.8 kV	1.6 kV	0.7 kV	0.8 kV	0.8 kV
		400 kV + 20 kV	11.2 MV (T1), 18.7 MV (T2)	1.71 MV	1.15 MV	863.9 kV	45 kV	61 kV	56.2 kV	6.7 kV	9.2 kV	8.2 kV	1 kV	1.5 kV	1.3 kV	0.7 kV	0.8 kV	0.8 kV
		400 kV + 20 kV + 6.9 kV	11.2 MV (T1), 18.7 MV (T2)	1.71 MV	1.15 MV	862.5 kV	45 kV	61 kV	56.2 kV	6.7 kV	9.2 kV	8.2 kV	1 kV	1.5 kV	1.3 kV	0.7 kV	0.8 kV	0.8 kV
3	1	None	18.4 MV (T1), 18.8 MV (T2), 19.8 MV (T3)	15 MV	10.7 MV	6 MV	495.4 kV	673.7 kV	601.4 kV	20.3 kV	24.6 kV	22.5 kV	3.1 kV	3.4 kV	3.2 kV	2 kV	2.1 kV	2 kV
		400 kV (All Phases)	14.3 MV (T1), 9.8 MV (T2), 9.6 MV (T3)	1.9 MV	918.5 kV	788.2 kV	43 kV	61.7 kV	57 kV	6.7 kV	7.3 kV	6.9 kV	3 kV	2.9 kV	2.9 kV	2 kV	2.1 kV	2 kV
		400 kV (Phase A)	14.3 MV (T1), 9.8 MV (T2), 9.6 MV (T3)	1.9 MV	2.42 MV	1.64 MV	71.5 kV	126 kV	110 kV	6.7 kV	7.3 kV	6.9 kV	3 kV	2.9 kV	2.9 kV	2 kV	2.1 kV	2 kV
		400 kV + 20 kV	14.3 MV (T1), 9.8 MV (T2), 9.6 MV (T3)	1.9 MV	918.5 kV	788.4 kV	40.1 kV	53.2 kV	49.2 kV	6.7 kV	7.3 kV	6.9 kV	3 kV	2.9 kV	2.9 kV	2 kV	2.1 kV	2 kV
		400 kV + 20 kV + 6.9 kV	14.3 MV (T1), 9.8 MV (T2), 9.6 MV (T3)	1.9 MV	918.5 kV	788.4 kV	40.1 kV	53.2 kV	49.2 kV	6.7 kV	7.3 kV	6.9 kV	3 kV	2.9 kV	2.9 kV	2 kV	2.1 kV	2 kV
	2	None	18.5 MV (T1), 19.3 MV (T2), 20 MV (T3)	15.1 MV	10.5 MV	5.83 MV	459.5 kV	669.3 kV	598.1 kV	20 kV	27.1 kV	24 kV	2.3 kV	2.9 kV	2.7 kV	1.1 kV	1.5 kV	1.3 kV
		400 kV (All Phases)	9 MV (T1), 16.5 MV (T2), 13.5 MV (T3)	1.57 MV	1.09 MV	874.3 kV	48.2 kV	70.1 kV	62.9 kV	6.5 kV	9 kV	8 kV	0.9 kV	1.5 kV	1.3 kV	0.8 kV	1 kV	0.8 kV
		400 kV (Phase A)	9.2 MV (T1), 16.5 MBV (T2), 13.5 MV (T3)	1.6 MV	2.86 MV	1.97 MV	82.6 kV	147.2 kV	128.5 kV	6.6 kV	9.1 kV	8.1 kV	0.9 kV	1.5 kV	1.3 kV	0.8 kV	1 kV	0.8 kV
		400 kV + 20 kV	10 MV (T1), 16.5 MV (T2), 13.5 MV (T3)	1.57 MV	1.09 MV	873.1 kV	43.1 kV	59.7 kV	54.5 kV	6.4 kV	8.8 kV	7.9 kV	0.9 kV	1.5 kV	1.3 kV	0.8 kV	1 kV	0.8 kV
		400 kV + 20 kV + 6.9 kV	11 MV (T1), 16.5 MV (T2), 13.5 MV (T3)	1.57 MV	1.09 MV	873.1 kV	43.1 kV	59.7 kV	54.5 kV	6.4 kV	8.8 kV	7.9 kV	0.9 kV	1.5 kV	1.3 kV	0.8 kV	1 kV	0.8 kV
	3	None	19.1 MV (T1), 19.7 MV (T2), 20.8 MV (T3)	15.8 MV	10.6 MV	5.91 MV	468.9 kV	680.1 kV	608.2 kV	26.5 kV	37.6 kV	33.5 kV	2.3 kV	3.3 kV	2.9 kV	1 kV	1.5 kV	1.3 kV
		400 kV (All Phases)	8.5 MV (T1), 12.7 MV (T2), 19.1 MV (T3)	1.55 MV	1.19 MV	913 kV	52.4 kV	78.4 kV	71.2 kV	6.3 kV	9.4 kV	8.4 kV	0.9 kV	1.3 kV	1.1 kV	0.5 kV	0.8 kV	0.7 kV
		400 kV (Phase A)	8.6 MV (T1), 12.7 MV (T2), 19.1 MV (T3)	1.56 MV	3.54 MV	2.45 MV	102.8 kV	181.7 kV	158.4 kV	6.9 kV	11.5 kV	9.7 kV	0.9 kV	1.3 kV	1.1 kV	0.5 kV	0.8 kV	0.7 kV
		400 kV + 20 kV	8.5 MV (T1), 12.7 MV (T2), 19.1 MV (T3)	1.55 MV	1.19 MV	913.9 kV	41.6 kV	56.4 kV	53.3 kV	5.7 kV	8.1 kV	7.3 kV	0.9 kV	1.3 kV	1.1 kV	0.5 kV	0.8 kV	0.7 kV
		400 kV + 20 kV + 6.9 kV	8.5 MV (T1), 12.7 MV (T2), 19.1 MV (T3)	1.55 MV	1.19 MV	913.9 kV	41.6 kV	56.4 kV	53.3 kV	5.7 kV	8.1 kV	7.3 kV	0.9 kV	1.3 kV	1.1 kV	0.5 kV	0.8 kV	0.7 kV
4	1	None	17.3 MV (T1), 15.4 MV (T2), 16.9 MV (T3), 16.6 MV (T4)	12.4 MV	9.1 MV	5.2 MV	388.7 kV	572.6 kV	506.5 kV	20.3 kV	24.6 kV	22.5 kV	3.1 kV	3.4 kV	3.2 kV	2 kV	2.1 kV	2 kV
		400 kV (All Phases)	14.3 MV (T1), 8.5 MV (T2), 8.4 MV (T3), 8 MV (T4)	1.9 MV	904.5 kV	777.2 kV	40.7 kV	59 kV	54.1 kV	6.7 kV	7.3 kV	6.9 kV	3 kV	2.9 kV	2.9 kV	2 kV	2.1 kV	2 kV
		400 kV (Phase A)	14.3 MV (T1), 8.5 MV (T2), 8.4 MV (T3), 8 MV (T4)	1.9 MV	2.2 MV	1.5 MV	66.5 kV	115.9 kV	101.5 kV	6.7 kV	7.3 kV	6.9 kV	3 kV	2.9 kV	2.9 kV	2 kV	2.1 kV	2 kV
		400 kV + 20 kV	14.3 MV (T1), 8.5 MV (T2), 8.4 MV (T3), 8 MV (T4)	1.9 MV	904 kV	777.2 kV	40.1 kV	51.6 kV	47.5 kV	6.7 kV	7.3 kV	6.9 kV	3 kV	2.9 kV	2.9 kV	2 kV	2.1 kV	2 kV
		400 kV + 20 kV + 6.9 kV	14.3 MV (T1), 8.5 MV (T2), 8.4 MV (T3), 8 MV (T4)	1.9 MV	904 kV	777.2 kV	40.1 kV	51.6 kV	47.5 kV	6.7 kV	7.3 kV	6.9 kV	3 kV	2.9 kV	2.9 kV	2 kV	2.1 kV	2 kV
	2	None	15.4 MV (T1), 16.5 MV (T2), 17 MV (T3), 16.2 MV (T4)	12.3 MV	8.7 MV	4.9 MV	376.9 kV	550.2 kV	492 kV	19.6 kV	26 kV	23.3 kV	2.3 kV	2.9 kV	2.6 kV	1.1 kV	1.5 kV	1.3 kV
		400 kV (All Phases)	8.5 MV (T1), 16.3 MV (T2), 10.7 MV (T3), 11.4 MV (T4)	1.56 MV	1.08 MV	824.2 kV	47.6 kV	69.3 kV	62.1 kV	6.5 kV	9 kV	8 kV	0.9 kV	1.4 kV	1.2 kV	0.7 kV	0.7 kV	0.7 kV
		400 kV (Phase A)	8.5 MV (T1), 16.3 MV (T2), 10.7 MV (T3), 11.4 MV (T4)	1.58 MV	2.5 MV	1.74 MV	74.1 kV	130.5 kV	114.3 kV	6.5 kV	9 kV	8 kV	0.9 kV	1.4 kV	1.2 kV	0.7 kV	0.7 kV	0.7 kV
		400 kV + 20 kV	8.5 MV (T1), 16.3 MV (T2), 10.7 MV (T3), 11.4 MV (T4)	1.56 MV	1.07 MV	824 kV	42.8 kV	59.4 kV	54.1 kV	6.4 kV	8..8 kV	7.9 kV	0.9 kV	1.4 kV	1.2 kV	0.7 kV	0.7 kV	0.7 kV
		400 kV + 20 kV + 6.9 kV	8.5 MV (T1), 16.3 MV (T2), 10.7 MV (T3), 11.4 MV (T4)	1.56 MV	1.07 MV	822.5 kV	42.8 kV	59.4 kV	54.1 kV	6.4 kV	8..8 kV	7.9 kV	0.9 kV	1.4 kV	1.2 kV	0.7 kV	0.7 kV	0.7 kV
	3	None	17.1 MV (T1), 17 MV (T2), 16.8 MV (T3), 18.1 MV (T4)	14.3 MV	9.8 MV	5.4 MV	430.3 kV	625.9 kV	558.8 kV	18.8 kV	27 kV	24 kV	1.8 kV	2.5 kV	2.3 kV	1 kV	1.3 kV	1.2 kV
		400 kV (All Phases)	7.7 MV (T1), 10.7 MV (T2), 16.8 MV (T3), 15.2 MV (T4)	1.47 MV	1.12 MV	921 kV	48.6 kV	73 kV	66.2 kV	5.9 kV	8.9 kV	7.9 kV	0.8 kV	1.1 kV	1.1 kV	0.5 kV	0.9 kV	0.8 kV
		400 kV (Phase A)	7.8 MV (T1), 10.7 MV (T2), 16.8 MV (T3), 15.2 MV (T4)	1.48 MV	3.28 MV	2.28 MV	95.2 kV	169.7 kV	148.2 kV	6.4 kV	9.8 kV	8.6 kV	0.8 kV	1.1 kV	1.1 kV	0.5 kV	0.9 kV	0.8 kV
		400 kV + 20 kV	7.7 MV (T1), 10.7 MV (T2), 16.8 MV (T3), 15.2 MV (T4)	1.47 MV	1.12 MV	919.6 kV	40.5 kV	56.1 kV	52.7 kV	5.5 kV	7.9 kV	7.2 kV	0.8 kV	1.1 kV	1.1 kV	0.5 kV	0.9 kV	0.8 kV
		400 kV + 20 kV + 6.9 kV	7.7 MV (T1), 10.7 MV (T2), 16.8 MV (T3), 15.2 MV (T4)	1.47 MV	1.12 MV	919.6 kV	40.5 kV	56.1 kV	52.7 kV	5.5 kV	7.9 kV	7.2 kV	0.8 kV	1.1 kV	1.1 kV	0.5 kV	0.9 kV	0.8 kV
	4	None	16.1 MV (T1), 16.2 MV (T2), 17.6 MV (T3), 19.1 MV (T4)	14.4 MV	10.1 MV	5.5 MV	432.5 kV	634.8 kV	566.1 kV	24.4 kV	35.1 kV	31.3 kV	2 kV	2.9 kV	2.5 kV	0.7 kV	1 kV	0.9 kV
		400 kV (All Phases)	7 MV (T1), 10.4 MV (T2), 14.3 MV (T3), 19.1 MV (T4)	1.48 MV	1.14 MV	968 kV	50.9 kV	76.9 kV	70.4 kV	5.6 kV	8.6 kV	8.7 kV	0.9 kV	1.2 kV	1.1 kV	0.4 kV	0.6 kV	0.5 kV
		400 kV (Phase A)	7.2 MV (T1), 10.6 MV (T2), 14.3 MV (T3), 19 MV (T4)	1.49 MV	3.84 MV	2.76 MV	110 kV	196 kV	177.2 kV	6.6 kV	11.6 kV	9.9 kV	0.9 kV	1.2 kV	1.1 kV	0.4 kV	0.6 kV	0.5 kV
		400 kV + 20 kV	7 MV (T1), 10.4 MV (T2), 14.3 MV (T3), 19.1 MV (T4)	1.47 MV	1.14 MV	965.5 kV	41.8 kV	58.7 kV	53.5 kV	4.7 kV	6.7 kV	6.2 kV	0.9 kV	1.2 kV	1.1 kV	0.4 kV	0.6 kV	0.5 kV
		400 kV + 20 kV + 6.9 kV	7 MV (T1), 10.4 MV (T2), 14.3 MV (T3), 19.1 MV (T4)	1.47 MV	1.14 MV	965.5 kV	41.8 kV	58.7 kV	53.5 kV	4.7 kV	6.7 kV	6.2 kV	0.9 kV	1.2 kV	1.1 kV	0.4 kV	0.6 kV	0.5 kV

Figure 4.20: Results for 200 kA 1.2/50 μs direct stroke to the ground wire with a surge capacitance.

Phase B and Phase C of 400 kV level values become more than BIL. Also, induced voltages in all phases of 20 kV level increase significantly. Phase B and Phase C of 20 kV become more than BIL for some scenarios. Phase A of 20 kV level is below BIL for all scenarios. Moreover, there is a slight increase in 6.9 kV level but the values are almost same as the values in Case 2.

– When one surge arrester in each phase of 400 kV and 20 kV levels is operating (Case 4), the magnitudes of the induced voltages in 400 kV level are similar as the operation of only 400 kV level surge arresters (Case 2). For 20 kV level, the induced voltage values reduce compared to Case 2. Moreover, there is a slight decrease in 6.9 kV level but the values are almost same as the values in Case 2. Since 20 kV level is already below BIL without operation of the surge arresters in 20 kV level (Case 2), using 20 kV level surge arresters is not necessary.

– When one surge arrester in each phase of 400 kV, 20 kV, and 6.9 kV levels is operating (Case 5), all results are the same as protection with only 400 kV and 20 kV surge arresters (Case 4) except for 6.9 kV level. The magnitude of 6.9 kV level slightly reduces for some scenarios; however, for most of the scenarios this level stays constant. Hence, there is no need to operate 6.9 kV level surge arresters as they don't have significant effect.

– In this simulation, Case 2 seems as the most reasonable case among the other cases. Although Phase A of 400 kV level is above BIL, the other phases of that level the other levels are below BIL. In order to make Phase A of 400 kV level below BIL, a surge arrester with different ratings might be preferred.

4.4.3 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase A Conductor Without a Surge Capacitance

In this part, the lightning source has been adjusted as 20 kA 1.2/50 μs and the Phase A conductor of the tower was exposed to the lightning stroke. No surge capacitance is used in the network. The simulation results will be given in Figure 4.21 on the next page.

For the results of different cases and scenarios in Figure 4.21, following discussions and comments can be made:

– When the lightning strikes to Phase A conductor of the towers without the operation of any surge arresters (Case 1), Phase A of 400 kV level is above BIL and Phase C is below BIL for all scenarios. Phase B of 400 kV level is above BIL for 1 and 2 existing towers scenarios, and for the other scenarios, it is below BIL. All phases of 20 kV level are above BIL for 1 existing tower scenario and below BIL for the other scenarios.

– When the lightning strikes to Phase A conductor of the towers without any protection (Case 1), in case of 1 existing towers, all phases of 20 kV level are

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 20 kV Side			Induced Voltage Peak on 6.9 kV Side			Induced Voltage Peak on 690 V Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	2.91 MV (T1)	2.9 MV	1.99 MV	1.1 MV	152.7 kV	186 kV	173.8 kV	5.2 kV	5.6 kV	5.3 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV (All Phases)	889.5 kV (T1)	902.2 kV	552 kV	302.3 kV	42.9 kV	52.1 kV	48.7 kV	4.3 kV	4.7 kV	4.5 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV (Phase A)	889.5 kV (T1)	902.2 kV	552.5 kV	302.5 kV	42.9 kV	52.1 kV	48.7 kV	4.3 kV	4.7 kV	4.5 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV + 20 kV	889.5 kV (T1)	902.2 kV	552 kV	302.3 kV	42.7 kV	51.9 kV	48.6 kV	4.3 kV	4.7 kV	4.5 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV + 20 kV + 6.9 kV	889.5 kV (T1)	902.2 kV	552 kV	302.3 kV	42.7 kV	51.9 kV	48.6 kV	4.3 kV	4.7 kV	4.5 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
2	1	None	2.08 MV (T1), 2.1 MV (T2)	2.06 MV	1.43 MV	791.9 kV	108.9 kV	133 kV	124.3 kV	4.9 kV	5.3 kV	5.1 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV (All Phases)	924.4 kV (T1), 1.04 MV (T2)	862.4 kV	606.9 kV	350.4 kV	44.8 kV	54.8 kV	51.2 kV	4.2 kV	4.6 kV	4.4 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV (Phase A)	924.4 kV (T1), 1.04 MV (T2)	862.4 kV	608.9 kV	350.9 kV	44.8 kV	54.8 kV	51.2 kV	4.2 kV	4.6 kV	4.4 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV + 20 kV	924.4 kV (T1), 1.04 MV (T2)	862.4 kV	606.9 kV	350.4 kV	44.5 kV	54.4 kV	50.9 kV	4.2 kV	4.6 kV	4.4 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV + 20 kV + 6.9 kV	924.4 kV (T1), 1.04 MV (T2)	862.4 kV	606.9 kV	350.4 kV	44.5 kV	54.4 kV	50.9 kV	4.2 kV	4.6 kV	4.4 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
	2	None	2.07 MV (T1), 2.27 MV (T2)	2.09 MV	1.41 MV	786.4 kV	108.7 kV	132.3 kV	123.8 kV	5.2 kV	6.2 kV	5.8 kV	0.5 kV	0.6 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (All Phases)	1.2 MV (T1), 1.1 MV (T2)	934.9 kV	703.1 kV	398.6 kV	48.8 kV	60.9 kV	56.3 kV	4.4 kV	5.2 kV	4.9 kV	0.5 kV	0.6 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (Phase A)	1.2 MV (T1), 1.1 MV (T2)	935 kV	738.1 kV	409.2 kV	49.3 kV	61.6 kV	57 kV	4.4 kV	5.2 kV	4.9 kV	0.5 kV	0.6 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
3	1	None	1.58 MV (T1), 1.6 MV (T2), 1.7 MV (T3)	1.63 MV	1.12 MV	633.7 kV	86.2 kV	105.2 kV	98.4 kV	4.9 kV	5.3 kV	5 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV (All Phases)	838.5 kV (T1), 1 MV (T2), 1.04 MV (T3)	858.8 kV	587.2 kV	348.9 kV	44.1 kV	54.3 kV	50.8 kV	4.2 kV	4.6 kV	4.3 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV (Phase A)	838.6 kV (T1), 1 MV (T2), 1.04 MV (T3)	858.8 kV	588.6 kV	349.3 kV	44.2 kV	54.4 kV	50.8 kV	4.2 kV	4.6 kV	4.3 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
	2	None	1.38 MV (T1), 1.7 MV (T2), 1.72 MV (T3)	1.61 MV	1.11 MV	616 kV	85.1 kV	103.8 kV	97 kV	3.8 kV	4.5 kV	4.2 kV	0.5 kV	0.5 kV	0.5 kV	0.2 kV	0.3 kV	0.2 kV
		400 kV (All Phases)	985.7 kV (T1), 1.25 MV (T2), 1.07 MV (T3)	837.1 kV	684.3 kV	412.5 kV	48.8 kV	61 kV	56.9 kV	3.8 kV	4.5 kV	4.2 kV	0.5 kV	0.5 kV	0.5 kV	0.2 kV	0.3 kV	0.2 kV
		400 kV (Phase A)	986.7 kV (T1), 1.26 MV (T2), 1.07 MV (T3)	837.1 kV	713.1 kV	419.9 kV	49.8 kV	61 kV	56.9 kV	3.8 kV	4.5 kV	4.2 kV	0.5 kV	0.5 kV	0.5 kV	0.2 kV	0.3 kV	0.2 kV
	3	None	1.64 MV (T1), 1.65 MV (T2), 1.83 MV (T3)	1.64 MV	1.13 MV	613.7 kV	86.1 kV	104.9 kV	98 kV	4.8 kV	5.8 kV	5.4 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (All Phases)	1.21 MV (T1), 1.04 MV (T2), 1.13 MV (T3)	872.1 kV	728.7 kV	455.2 kV	50.9 kV	63.7 kV	59.2 kV	4 kV	4.9 kV	4.6 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (Phase A)	1.21 MV (T1), 1.04 MV (T2), 1.13 MV (T3)	872.1 kV	801.6 kV	476.2 kV	51.6 kV	65.5 kV	60.5 kV	5 kV	4.9 kV	4.6 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
4	1	None	1.31 MV (T1), 1.28 MV (T2), 1.45 MV (T3), 1.54 MV (T4)	1.35 MV	925.2 kV	531 kV	71.6 kV	87.3 kV	81.6 kV	4.9 kV	5.3 kV	5 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV (All Phases)	773.3 kV (T1), 826.5 kV (T2), 1 MV (T3), 960.7 kV (T4)	858.8 kV	546.2 kV	322.4 kV	41.4 kV	50.8 kV	47.6 kV	4.2 kV	4.6 kV	4.3 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
		400 kV (Phase A)	773.3 kV (T1), 826.5 kV (T2), 1 MV (T3), 960.7 kV (T4)	858.8 kV	546.8 kV	322.5 kV	41.4 kV	50.8 kV	47.6 kV	4.2 kV	4.6 kV	4.3 kV	0.9 kV	0.9 kV	0.9 kV	0.6 kV	0.6 kV	0.6 kV
	2	None	1.28 MV (T1), 1.42 MV (T2), 1.44 MV (T3), 1.41 MV (T4)	1.33 MV	899.2 kV	496 kV	69.6 kV	84.7 kV	79.2 kV	3.7 kV	4.4 kV	4.1 kV	0.5 kV	0.5 kV	0.5 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	888.3 kV (T1), 934.6 kV (T2), 1.24 MV (T3), 1.02 MV (T4)	820.3 kV	618.2 kV	362.1 kV	44.7 kV	55.4 kV	51.6 kV	3.7 kV	4.4 kV	4.1 kV	0.5 kV	0.5 kV	0.5 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (Phase A)	888.3 kV (T1), 934.6 kV (T2), 1.24 MV (T3), 1.02 MV (T4)	820.3 kV	622.5 kV	363.4 kV	44.8 kV	55.6 kV	51.7 kV	3.7 kV	4.4 kV	4.1 kV	0.5 kV	0.5 kV	0.5 kV	0.2 kV	0.2 kV	0.2 kV
	3	None	1.46 MV (T1), 1.42 MV (T2), 1.46 MV (T3), 1.55 MV (T4)	1.42 MV	1.03 MV	565.1 kV	76.9 kV	94.4 kV	88 kV	3.3 kV	4.1 kV	3.8 kV	0.4 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	1.02 MV (T1), 1.3 MV (T2), 1.04 MV (T3), 1.18 MV (T4)	805.9 kV	702.4 kV	439.6 kV	49.4 kV	62.1 kV	57.9 kV	3.3 kV	4.1 kV	3.8 kV	0.4 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (Phase A)	1.02 MV (T1), 1.3 MV (T2), 1.04 MV (T3), 1.18 MV (T4)	806 kV	754.5 kV	453.8 kV	51.1 kV	64.8 kV	60.2 kV	3.3 kV	4.1 kV	3.8 kV	0.4 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
	4	None	1.43 MV (T1), 1.39 MV (T2), 1.49 MV (T3), 1.52 MV (T4)	1.38 MV	1.04 MV	586.1 kV	76.4 kV	94.4 kV	88 kV	4.3 kV	5.2 kV	4.9 kV	0.4 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	1.15 MV (T1), 1 MV (T2), 1.13 MV (T3), 1.21 MV (T4)	860.8 kV	725.5 kV	460.4 kV	50.3 kV	62.8 kV	58.4 kV	3.8 kV	4.7 kV	4.4 kV	0.4 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (Phase A)	1.15 MV (T1), 1 MV (T2), 1.13 MV (T3), 1.21 MV (T4)	862.3 kV	786.8 kV	485.5 kV	50.8 kV	65.3 kV	60.4 kV	3.8 kV	4.7 kV	4.4 kV	0.4 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV

Figure 4.21: Results for 20 kA 1.2/50 μs direct stroke to the Phase A conductor without a surge capacitance.

above BIL. For the other scenarios, all phases of 20 kV level are below BIL. Moreover, all phases of 6.9 kV level are below BIL for all scenarios.

- As the number of towers increase, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage magnitude on each level is below BIL.
- When one surge arrester in Phase A of 400 kV level is operating (Case 3), the results are slightly more than the results in Case 2. Induced voltage on each level is below BIL.
- When one surge arrester in each phase of 400 kV and 20 kV levels is operating (Case 4), the results are similar as Case 2. Operation of the surge arresters in 20 kV level does not have significant effect. Therefore, this case hasn't been simulated for the next studies.
- When one surge arrester in each phase of 400 kV, 20 kV, and 6.9 kV levels is operating (Case 5), the results are almost the same as Case 2 and Case 4. Operation of the surge arresters in 6.9 kV level does not have significant effect. Therefore, this case hasn't been simulated for the next studies.
- As a result, the surge arresters in 20 kV and 6.9 kV level don't affect the voltage levels significantly if 400 kV surge arresters are operating. One surge arrester operation in Phase A of 400 kV level (Case 3) is sufficient to make the system safe as each voltage level is below BIL.

4.4.4 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase A Conductor With a Surge Capacitance

In this part, the lightning source has been adjusted as 20 kA 1.2/50 μs and the Phase A conductor of the tower was exposed to lightning stroke. A surge capacitance of 0.36 μF is used in the network. The results are demonstrated in Figure 4.22 on the next page.

For the results of different cases and scenarios in Figure 4.22, following discussions and comments can be made:

- For all scenarios, the values in 400 kV level are almost the same as the case without a surge capacitance; whereas, the values in 20 kV and 6.9 kV level are significantly less than the case without a surge capacitance.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 20 kV Side			Induced Voltage Peak on 6.9 kV Side			Induced Voltage Peak on 690 V Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	2.9 MV (T1)	2.9 MV	1.98 MV	1.09 MV	86.7 kV	126.6 kV	113.1 kV	2.9 kV	3.6 kV	3.2 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (All Phases)	888.4 kV (T1)	903 kV	552.3 kV	302.3 kV	24.2 kV	33.8 kV	31 kV	2.4 kV	3 kV	2.7 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (Phase A)	889.5 kV (T1)	902.2 kV	552.6 kV	302.5 kV	24.6 kV	34.5 kV	31.7 kV	2.4 kV	3 kV	2.7 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
2	1	None	2.08 MV (T1), 2.1 MV (T2)	2.1 MV	1.43 MV	789.8 kV	62.2 kV	90.7 kV	81 kV	2.8 kV	3.4 kV	3.1 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (All Phases)	924.4 kV (T1), 1.04 MV (T2)	862.4 kV	606.9 kV	350.4 kV	25 kV	36.1 kV	32.5 kV	2.4 kV	3 kV	2.7 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (Phase A)	924.4 kV (T1), 1.04 MV (T2)	862.4 kV	608.9 kV	350.9 kV	25.6 kV	37.4 kV	33.4 kV	2.4 kV	3 kV	2.7 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
	2	None	2.07 MV (T1), 2.27 MV (T2)	2.09 MV	1.41 MV	786.4 kV	62 kV	90.3 kV	80.7 kV	2.9 kV	4.2 kV	3.7 kV	0.3 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	1.2 MV (T1), 1.1 MV (T2)	934.9 kV	703.1 kV	398.1 kV	27.5 kV	41 kV	36.2 kV	2.5 kV	3.5 kV	3.1 kV	0.3 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (Phase A)	1.2 MV (T1), 1.1 MV (T2)	935 kV	738.1 kV	408.3 kV	28.1 kV	42.4 kV	37.3 kV	2.5 kV	3.5 kV	3.1 kV	0.3 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
3	1	None	1.58 MV (T1), 1.6 MV (T2), 1.7 MV (T3)	1.63 MV	1.12 MV	632.5 kV	49.2 kV	71.6 kV	64.1 kV	2.8 kV	3.4 kV	3.1 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (All Phases)	838.5 kV (T1), 1 MV (T2), 1.04 MV (T3)	856.3 kV	588.7 kV	349.5 kV	24.7 kV	36.1 kV	32.4 kV	2.4 kV	2.9 kV	2.7 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (Phase A)	838.6 kV (T1), 1 MV (T2), 1.04 MV (T3)	856.3 kV	587.4 kV	349.1 kV	25.3 kV	37.2 kV	33.3 kV	2.4 kV	2.9 kV	2.7 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
	2	None	1.38 MV (T1), 1.7 MV (T2), 1.72 MV (T3)	1.61 MV	1.11 MV	615.2 kV	48.7 kV	70.8 kV	63.3 kV	2.2 kV	3 kV	2.6 kV	0.3 kV	0.3 kV	0.3 kV	0.15 kV	0.15 kV	0.15 kV
		400 kV (All Phases)	985.7 kV (T1), 1.25 MV (T2), 1.07 MV (T3)	834.2 kV	684.2 kV	412.6 kV	27.9 kV	42.1 kV	37.5 kV	2.2 kV	3 kV	2.6 kV	0.3 kV	0.3 kV	0.3 kV	0.15 kV	0.15 kV	0.15 kV
		400 kV (Phase A)	986.7 kV (T1), 1.26 MV (T2), 1.07 MV (T3)	834.2 kV	712.7 kV	419.8 kV	28.5 kV	43.6 kV	38.4 kV	2.2 kV	3 kV	2.6 kV	0.3 kV	0.3 kV	0.3 kV	0.15 kV	0.15 kV	0.15 kV
	3	None	1.64 MV (T1), 1.65 MV (T2), 1.83 MV (T3)	1.64 MV	1.13 MV	612.5 kV	49.2 kV	71.5 kV	63.7 kV	2.3 kV	3.4 kV	3.1 kV	0.25 kV	0.3 kV	0.3 kV	0.2 kV	0.25 kV	0.2 kV
		400 kV (All Phases)	1.21 MV (T1), 1.04 MV (T2), 1.13 MV (T3)	868.9 kV	726 kV	454.8 kV	29.1 kV	43.9 kV	38.9 kV	2.3 kV	3.4 kV	3.1 kV	0.25 kV	0.3 kV	0.3 kV	0.2 kV	0.25 kV	0.2 kV
		400 kV (Phase A)	1.21 MV (T1), 1.04 MV (T2), 1.13 MV (T3)	870.5 kV	800.9 kV	476.6 kV	29.5 kV	45.9 kV	40.4 kV	2.3 kV	3.4 kV	3.1 kV	0.25 kV	0.3 kV	0.3 kV	0.2 kV	0.25 kV	0.2 kV
4	1	None	1.31 MV (T1), 1.28 MV (T2), 1.45 MV (T3), 1.54 MV (T4)	1.35 MV	923.6 kV	529.6 kV	40.9 kV	59.4 kV	53.2 kV	2.8 kV	3.4 kV	3.1 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (All Phases)	773.3 kV (T1), 826.5 kV (T2), 1 MV (T3), 960.7 kV (T4)	856.3 kV	546.3 kV	322.5 kV	23.7 kV	34.8 kV	31.2 kV	2.4 kV	2.9 kV	2.7 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
		400 kV (Phase A)	773.3 kV (T1), 826.5 kV (T2), 1 MV (T3), 960.7 kV (T4)	856.2 kV	546.6 kV	319.2 kV	23.7 kV	34.8 kV	31.2 kV	2.4 kV	2.9 kV	2.7 kV	0.5 kV	0.5 kV	0.5 kV	0.3 kV	0.3 kV	0.3 kV
	2	None	1.28 MV (T1), 1.42 MV (T2), 1.44 MV (T3), 1.41 MV (T4)	1.33 MV	898.2 kV	495.7 kV	39.8 kV	57.7 kV	51.6 kV	2.1 kV	2.9 kV	2.6 kV	0.3 kV	0.3 kV	0.3 kV	0.15 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	888.3 kV (T1), 934.6 kV (T2), 1.24 MV (T3), 1.02 MV (T4)	817.3 kV	618.8 kV	362.8 kV	25.5 kV	38.2 kV	34 kV	2.1 kV	2.9 kV	2.6 kV	0.3 kV	0.3 kV	0.3 kV	0.15 kV	0.2 kV	0.2 kV
		400 kV (Phase A)	888.3 kV (T1), 934.6 kV (T2), 1.24 MV (T3), 1.02 MV (T4)	819.5 kV	623.2 kV	364.1 kV	25.7 kV	38.3 kV	34.1 kV	2.1 kV	2.9 kV	2.6 kV	0.3 kV	0.3 kV	0.3 kV	0.15 kV	0.2 kV	0.2 kV
	3	None	1.46 MV (T1), 1.42 MV (T2), 1.46 MV (T3), 1.55 MV (T4)	1.42 MV	1.02 MV	563.4 kV	43.9 kV	64.5 kV	57.5 kV	1.9 kV	2.8 kV	2.5 kV	0.2 kV	0.25 kV	0.25 kV	0.1 kV	0.15 kV	0.15 kV
		400 kV (All Phases)	1.02 MV (T1), 1.3 MV (T2), 1.04 MV (T3), 1.18 MV (T4)	805.5 kV	702.7 kV	440 kV	28.2 kV	43 kV	38.4 kV	1.9 kV	2.8 kV	2.5 kV	0.2 kV	0.25 kV	0.25 kV	0.1 kV	0.15 kV	0.15 kV
		400 kV (Phase A)	1.02 MV (T1), 1.3 MV (T2), 1.04 MV (T3), 1.18 MV (T4)	806.9 kV	754.4 kV	453.8 kV	29.2 kV	45.1 kV	40 kV	1.9 kV	2.8 kV	2.5 kV	0.2 kV	0.25 kV	0.25 kV	0.1 kV	0.15 kV	0.15 kV
	4	None	1.43 MV (T1), 1.39 MV (T2), 1.49 MV (T3), 1.52 MV (T4)	1.38 MV	1.04 MV	584.5 kV	43.6 kV	64.7 kV	57.6 kV	2.2 kV	3.2 kV	2.9 kV	0.25 kV	0.3 kV	0.25 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	1.15 MV (T1), 1 MV (T2), 1.13 MV (T3), 1.21 MV (T4)	861.5 kV	726.6 kV	459.7 kV	28.7 kV	43.4 kV	38.6 kV	2.2 kV	3.2 kV	2.9 kV	0.25 kV	0.3 kV	0.25 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (Phase A)	1.15 MV (T1), 1 MV (T2), 1.13 MV (T3), 1.21 MV (T4)	862.9 kV	785.7 kV	485.7 kV	29 kV	45.6 kV	40.3 kV	2.2 kV	3.2 kV	2.9 kV	0.25 kV	0.3 kV	0.25 kV	0.2 kV	0.2 kV	0.2 kV

Figure 4.22: Results for 20 kA 1.2/50 μs direct stroke to the Phase A conductor with a surge capacitance.

- When the lightning strikes to Phase A conductor of the towers without the operation of any surge arresters (Case 1), in case of 1 existing tower, Phase A and Phase B of 400 kV level are above BIL. In case of 2, 3, and 4 existing towers, Phase A of 400 kV level is above BIL; whereas, Phase B and Phase C of 400 kV level are below BIL. In 20 kV level, all phases are below BIL for all scenarios. Moreover, all phases of 6.9 kV level are below BIL for all scenarios.
- As the number of towers increase, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage on each level is below BIL.
- When one surge arrester in Phase A of 400 kV level is operating (Case 3), the results are almost the same as the results in Case 2. Induced voltage on each level is below BIL.
- As a result, one surge arrester operation in Phase A of 400 kV level (Case 3) is sufficient to make the system safe as each voltage level is below BIL.

4.4.5 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase B Conductor Without a Surge Capacitance

In this part, the lightning source has been adjusted as 20 kA 1.2/50 μs and Phase B conductor of the tower was exposed to the lightning stroke. No surge capacitance is used in the network. The simulation results will be given in Figure 4.23 on the next page.

For the results of different cases and scenarios in Figure 4.23, following discussions and comments can be made:

- When the lightning strikes to the Phase B conductor of the towers without the operation of any surge arresters (Case 1), Phase C of 400 kV level is below BIL for all scenarios. Phase A and Phase B of 400 kV level are above BIL for 1 and 2 existing towers scenarios and they are below BIL for the other scenarios. Phase B and Phase C of 20 kV level are above BIL for 1 existing tower scenario and below BIL for the other scenarios. Moreover, all phases of 6.9 kV level are below BIL for all scenarios.
- As the number of towers increases, the magnitude of the induced voltages on each level decreases.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 20 kV Side			Induced Voltage Peak on 6.9 kV Side			Induced Voltage Peak on 690 V Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	2.25 MV (T1)	2.25 MV	2.29 MV	1.27 MV	146.5 kV	187.9 kV	173.3 kV	5.1 kV	7.4 kV	6.4 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
		400 kV (All Phases)	699.2 kV (T1)	692.9 kV	871.4 kV	446.4 kV	48.8 kV	63.6 kV	58.4 kV	4.6 kV	6.6 kV	5.8 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
		400 kV (Phase B)	787.7 kV (T1)	789.1 kV	871.5 kV	448.2 kV	51.4 kV	66 kV	60.8 kV	4.6 kV	6.6 kV	5.8 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
2	1	None	1.54 MV (T1), 1.57 MV (T2)	1.55 MV	1.53 MV	859.8 kV	99.7 kV	127.3 kV	117.6 kV	4.9 kV	7 kV	6.1 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
		400 kV (All Phases)	777.7 kV (T1), 753.8 kV (T2)	734.8 kV	828.6 kV	453.2 kV	49.6 kV	64 kV	58.9 kV	4.5 kV	6.4 kV	5.6 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
		400 kV (Phase B)	841.6 kV (T1), 854 kV (T2)	835.1 kV	828.6 kV	456.9 kV	52.3 kV	66.2 kV	61.4 kV	4.5 kV	6.4 kV	5.6 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
	2	None	1.59 MV (T1), 1.68 MV (T2)	1.56 MV	1.57 MV	852.5 kV	100.5 kV	128.4 kV	118.5 kV	4.8 kV	6.2 kV	5.7 kV	0.5 kV	0.6 kV	0.5 kV	0.25 kV	0.3 kV	0.3 kV
		400 kV (All Phases)	779.1 kV (T1), 941.9 kV (T2)	790.7 kV	870.4 kV	589.1 kV	56.2 kV	72.6 kV	67.4 kV	4.5 kV	5.8 kV	5.3 kV	0.5 kV	0.6 kV	0.5 kV	0.25 kV	0.3 kV	0.3 kV
		400 kV (Phase B)	912.6 kV (T1), 1.12 MV (T2)	914.2 kV	875.7 kV	595.1 kV	58.5 kV	74.3 kV	69.3 kV	4.5 kV	5.8 kV	5.3 kV	0.5 kV	0.6 kV	0.5 kV	0.25 kV	0.3 kV	0.3 kV
3	1	None	1.18 MV (T1), 1.18 MV (T2), 1.23 MV (T3)	1.18 MV	1.18 MV	637 kV	75.7 kV	96.8 kV	89.2 kV	4.9 kV	7 kV	6.1 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
		400 kV (All Phases)	777.9 kV (T1), 772.7 kV (T2), 806.9 kV (T3)	721 kV	826 kV	412.1 kV	47.8 kV	61.5 kV	56.5 kV	4.5 kV	6.4 kV	5.6 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
		400 kV (Phase B)	825.5 kV (T1), 788.3 kV (T2), 807.1 kV (T3)	809.6 kV	826 kV	421.4 kV	50.4 kV	64 kV	59.2 kV	4.5 kV	6.4 kV	5.6 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
	2	None	1.2 MV (T1), 1.25 MV (T2), 1.26 MV (T3)	1.2 MV	1.19 MV	652.1 kV	76.9 kV	98.2 kV	90.6 kV	3.5 kV	4.6 kV	4.2 kV	0.4 kV	0.5 kV	0.5 kV	0.25 kV	0.3 kV	0.25 kV
		400 kV (All Phases)	802.4 kV (T1), 963.3 kV (T2), 808.3 kV (T3)	749.1 kV	785 kV	508 kV	50.7 kV	65 kV	60.5 kV	3.5 kV	4.6 kV	4.2 kV	0.4 kV	0.5 kV	0.5 kV	0.25 kV	0.3 kV	0.25 kV
		400 kV (Phase B)	877 kV (T1), 970.3 kV (T2), 932.4 kV (T3)	886.7 kV	788.2 kV	504 kV	54.5 kV	68.5 kV	64 kV	3.5 kV	4.6 kV	4.2 kV	0.4 kV	0.5 kV	0.5 kV	0.25 kV	0.3 kV	0.25 kV
	3	None	1.22 MV (T1), 1.21 MV (T2), 1.39 MV (T3)	1.23 MV	1.20 MV	707 kV	78.5 kV	100.1 kV	92.4 kV	4.2 kV	5.3 kV	4.9 kV	0.4 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	883.7 kV (T1), 807.6 kV (T2), 849.1 kV (T3)	811 kV	795.4 kV	579.3 kV	54 kV	69.4 kV	64.9 kV	4.2 kV	5.3 kV	4.9 kV	0.4 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
		400 kV (Phase B)	968 kV (T1), 916.8 kV (T2), 1.05 MV (T3)	995.1 kV	820.5 kV	587.6 kV	61 kV	76.3 kV	71.7 kV	4.2 kV	5.3 kV	4.9 kV	0.4 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
4	1	None	993.3 kV (T1), 946.8 kV (T2), 1.03 MV (T3), 1.09 MV (T4)	973.3 kV	1.09 MV	500.2 kV	61.6 kV	78.6 kV	72.4 kV	4.9 kV	7 kV	6.1 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
		400 kV (All Phases)	729.5 kV (T1), 708.8 kV (T2), 775 kV (T3), 788.1 kV (T4)	691.8 kV	825.9 kV	377.4 kV	45.7 kV	58.8 kV	54 kV	4.5 kV	6.3 kV	5.6 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
		400 kV (Phase B)	761.9 kV (T1), 749.3 kV (T2), 775.1 kV (T3), 788.2 kV (T4)	745.5 kV	825.9 kV	383.4 kV	47.2 kV	60.3 kV	55.5 kV	4.5 kV	6.3 kV	5.6 kV	0.9 kV	1.3 kV	1.1 kV	0.6 kV	0.8 kV	0.7 kV
	2	None	956.7 kV (T1), 1.07 MV (T2), 1.07 MV (T3), 1.04 MV (T4)	937.3 kV	998.6 kV	525.2 kV	61.7 kV	79.7 kV	73.2 kV	3.5 kV	4.5 kV	4.2 kV	0.4 kV	0.5 kV	0.5 kV	0.2 kV	0.25 kV	0.2 kV
		400 kV (All Phases)	748.1 kV (T1), 853.9 kV (T2), 921.9 kV (T3), 791.7 kV (T4)	714.7 kV	751.5 kV	439.1 kV	47.5 kV	61.2 kV	56.4 kV	3.5 kV	4.5 kV	4.2 kV	0.4 kV	0.5 kV	0.5 kV	0.2 kV	0.25 kV	0.2 kV
		400 kV (Phase B)	795.5 kV (T1), 902.3 kV (T2), 923 kV (T3), 823.9 kV (T4)	779.7 kV	757.6 kV	439.3 kV	49.5 kV	63.1 kV	58.3 kV	3.5 kV	4.5 kV	4.2 kV	0.4 kV	0.5 kV	0.5 kV	0.2 kV	0.25 kV	0.2 kV
	3	None	1.07 MV (T1), 1.05 MV (T2), 1.12 MV (T3), 1.18 MV (T4)	1.04 MV	1.03 MV	613.6 kV	67.9 kV	86.8 kV	80.4 kV	2.9 kV	3.8 kV	3.5 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.15 kV	0.15 kV
		400 kV (All Phases)	830.3 kV (T1), 1.01 MV (T2), 792.3 kV (T3), 765.9 kV (T4)	763.6 kV	760.2 kV	521.7 kV	51.3 kV	65.6 kV	61.1 kV	2.9 kV	3.8 kV	3.5 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.15 kV	0.15 kV
		400 kV (Phase B)	973.8 kV (T1), 1.04 MV (T2), 917.3 kV (T3), 918.3 kV (T4)	947.4 kV	774 kV	530.1 kV	57 kV	71.1 kV	66.8 kV	2.9 kV	3.8 kV	3.5 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.15 kV	0.15 kV
	4	None	1.06 MV (T1), 1.02 MV (T2), 1.13 MV (T3), 1.2 MV (T4)	1.03 MV	984.9 kV	624.5 kV	66.5 kV	84.7 kV	78.8 kV	3.6 kV	4.5 kV	4.2 kV	0.3 kV	0.4 kV	0.4 kV	0.1 kV	0.15 kV	0.12 kV
		400 kV (All Phases)	917.8 kV (T1), 771.9 kV (T2), 823.6 kV (T3), 784.6 kV (T4)	790.9 kV	758.2 kV	538.1 kV	51.7 kV	66 kV	61.6 kV	3.6 kV	4.5 kV	4.2 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.15 kV
		400 kV (Phase B)	1.02 MV (T1), 864.6 kV (T2), 948.7 kV (T3), 995.7 kV (T4)	973.2 kV	783.1 kV	551.6 kV	58.1 kV	72.2 kV	68 kV	3.6 kV	4.5 kV	4.2 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.15 kV

Figure 4.23: Results for 20 kA 1.2/50 μs direct stroke to the Phase B conductor without a surge capacitance.

- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.

- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage on each level is below BIL.

- When one surge arrester in Phase B of 400 kV level is operating (Case 6), the results are slightly higher than Case 2 for Phase A of 400 kV level and all phases of 20 kV level; whereas, Phase B and Phase C of 400 kV level are almost same. Induced voltage on each level is below BIL.

- As a result, one surge arrester operation in Phase B of 400 kV level (Case 6) is sufficient to make the system safe as each voltage level is below BIL.

4.4.6 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase B Conductor With a Surge Capacitance

In this part, the lightning source has been adjusted as 20 kA 1.2/50 μs and the Phase B conductor of the tower was exposed to lightning stroke. A surge capacitance of 0.36 μF is used in the network. The results are demonstrated in Figure 4.24 on the next page.

For the results of different cases and scenarios in Figure 4.24, following discussions and comments can be made:

- For all scenarios, the values in 400 kV level are almost the same as the case without a surge capacitance; whereas, the values in 20 kV and 6.9 kV level are significantly less than the case without a surge capacitance.

- When the lightning strikes to the Phase B conductor of the towers without the operation of any surge arresters (Case 1), Phase C of 400 kV level is below BIL for all scenarios. Phase A and Phase B of 400 kV level are above BIL for 1 and 2 existing towers scenarios and they are below BIL for the other scenarios. In 20 kV level, all phases are below BIL for all scenarios. Moreover, all phases of 6.9 kV level are below BIL for all scenarios.

- As the number of towers increase, the magnitude of the induced voltages on each level decreases.

- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.

- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage on each level is below BIL.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 20 kV Side			Induced Voltage Peak on 6.9 kV Side			Induced Voltage Peak on 690 V Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	2.25 MV (T1)	2.24 MV	2.29 MV	1.26 MV	83.6 kV	130.8 kV	114.8 kV	2.9 kV	5.3 kV	4.3 kV	0.5 kV	1 kV	0.8 kV	0.3 kV	0.6 kV	0.5 kV
		400 kV (All Phases)	699.2 kV (T1)	692.6 kV	871.2 kV	446 kV	27.9 kV	44.7 kV	39 kV	2.6 kV	4.8 kV	3.9 kV	0.5 kV	1 kV	0.8 kV	0.3 kV	0.6 kV	0.5 kV
		400 kV (Phase B)	787.7 kV (T1)	788.9 kV	871.2 kV	447.7 kV	29.4 kV	46.1 kV	40.4 kV	2.6 kV	4.8 kV	3.9 kV	0.5 kV	1 kV	0.8 kV	0.3 kV	0.6 kV	0.5 kV
2	1	None	1.54 MV (T1), 1.57 MV (T2)	1.55 MV	1.53 MV	857.7 kV	56.9 kV	88.5 kV	78 kV	2.8 kV	5.1 kV	4.1 kV	0.5 kV	1 kV	0.7 kV	0.3 kV	0.6 kV	0.5 kV
		400 kV (All Phases)	777.7 kV (T1), 753.8 kV (T2)	734.9 kV	828.5 kV	453.1 kV	28.4 kV	44.8 kV	39.3 kV	2.5 kV	4.6 kV	3.8 kV	0.5 kV	1 kV	0.7 kV	0.3 kV	0.6 kV	0.5 kV
		400 kV (Phase B)	841.6 kV (T1), 854 kV (T2)	834.8 kV	828.5 kV	457.1 kV	29.9 kV	46 kV	40.8 kV	2.5 kV	4.6 kV	3.8 kV	0.5 kV	1 kV	0.7 kV	0.3 kV	0.6 kV	0.5 kV
	2	None	1.59 MV (T1), 1.68 MV (T2)	1.56 MV	1.57 MV	850.9 kV	57.5 kV	89.4 kV	78.6 kV	2.7 kV	4.3 kV	3.8 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	779.1 kV (T1), 941.9 kV (T2)	788.4 kV	870 kV	589.1 kV	32 kV	50.7 kV	45 kV	2.5 kV	4 kV	3.5 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
		400 kV (Phase B)	912.6 kV (T1), 1.12 MV (T2)	911.5 kV	874.8 kV	594.3 kV	33.5 kV	51.7 kV	46.2 kV	2.5 kV	4 kV	3.5 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
3	1	None	1.18 MV (T1), 1.18 MV (T2), 1.23 MV (T3)	1.18 MV	1.18 MV	636.2 kV	43.3 kV	67.4 kV	59.2 kV	2.8 kV	5.1 kV	4.1 kV	0.5 kV	1 kV	0.7 kV	0.3 kV	0.6 kV	0.5 kV
		400 kV (All Phases)	777.9 kV (T1), 772.7 kV (T2), 806.9 kV (T3)	720.6 kV	825.9 kV	412.2 kV	27.3 kV	43 kV	37.6 kV	2.5 kV	4.6 kV	3.8 kV	0.5 kV	2 kV	0.7 kV	0.3 kV	0.6 kV	0.5 kV
		400 kV (Phase B)	825.5 kV (T1), 788.3 kV (T2), 807.1 kV (T3)	808.9 kV	825.9 kV	421.4 kV	28.9 kV	44.5 kV	39.2 kV	2.5 kV	4.6 kV	3.8 kV	0.5 kV	3 kV	0.7 kV	0.3 kV	0.6 kV	0.5 kV
	2	None	1.2 MV (T1), 1.25 MV (T2), 1.26 MV (T3)	1.2 MV	1.19 MV	651.3 kV	44 kV	68.3 kV	60.1 kV	2 kV	3.2 kV	2.8 kV	0.2 kV	0.4 kV	0.3 kV	0.1 kV	0.2 kV	0.16 kV
		400 kV (All Phases)	802.4 kV (T1), 963.3 kV (T2), 808.3 kV (T3)	749.8 kV	785.7 kV	501.3 kV	29.1 kV	45.5 kV	40.4 kV	2 kV	3.2 kV	2.8 kV	0.2 kV	0.4 kV	0.3 kV	0.1 kV	0.2 kV	0.16 kV
		400 kV (Phase B)	877 kV (T1), 970.3 kV (T2), 932.4 kV (T3)	886.1 kV	789 kV	504.1 kV	31.2 kV	47.4 kV	42.4 kV	2 kV	3.2 kV	2.8 kV	0.2 kV	0.4 kV	0.3 kV	0.1 kV	0.2 kV	0.16 kV
	3	None	1.22 MV (T1), 1.21 MV (T2), 1.39 MV (T3)	1.23 MV	1.20 MV	705.1 kV	44.8 kV	69.6 kV	61.1 kV	2.4 kV	3.6 kV	3.2 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.13 kV	0.12 kV
		400 kV (All Phases)	883.7 kV (T1), 807.6 kV (T2), 849.1 kV (T3)	808.9 kV	797 kV	578.1 kV	31 kV	48.5 kV	43.6 kV	2.3 kV	3.6 kV	3.2 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.13 kV	0.12 kV
		400 kV (Phase B)	968 kV (T1), 916.8 kV (T2), 1.05 MV (T3)	991.1 kV	821.1 kV	587.1 kV	34.9 kV	52.6 kV	47.5 kV	2.3 kV	3.6 kV	3.2 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.13 kV	0.12 kV
4	1	None	993.3 kV (T1), 946.8 kV (T2), 1.03 MV (T3), 1.09 MV (T4)	971.4 kV	1.08 MV	499.8 kV	35.2 kV	54.7 kV	47.9 kV	2.8 kV	5.1 kV	4.1 kV	0.5 kV	1 kV	0.7 kV	0.3 kV	0.6 kV	0.5 kV
		400 kV (All Phases)	729.5 kV (T1), 708.8 kV (T2), 775 kV (T3), 788.1 kV (T4)	692.1 kV	825.8 kV	377.5 kV	26.1 kV	41.2 kV	35.9 kV	2.5 kV	4.6 kV	3.8 kV	0.5 kV	1 kV	0.7 kV	0.3 kV	0.6 kV	0.5 kV
		400 kV (Phase B)	761.9 kV (T1), 749.3 kV (T2), 775.1 kV (T3), 788.2 kV (T4)	745.7 kV	825.8 kV	383.4 kV	27 kV	42 kV	36.8 kV	2.5 kV	4.6 kV	3.8 kV	0.5 kV	1 kV	0.7 kV	0.3 kV	0.6 kV	0.5 kV
	2	None	956.7 kV (T1), 1.07 MV (T2), 1.07 MV (T3), 1.04 MV (T4)	935.8 kV	997.9 kV	524.9 kV	35.3 kV	55.8 kV	48.7 kV	2 kV	3.2 kV	2.8 kV	0.2 kV	0.4 kV	0.3 kV	0.12 kV	0.2 kV	0.15 kV
		400 kV (All Phases)	748.1 kV (T1), 853.9 kV (T2), 921.9 kV (T3), 791.7 kV (T4)	714.7 kV	751 kV	438 kV	27.2 kV	42.8 kV	37.6 kV	2 kV	3.2 kV	2.8 kV	0.2 kV	0.4 kV	0.3 kV	0.12 kV	0.2 kV	0.15 kV
		400 kV (Phase B)	795.5 kV (T1), 902.3 kV (T2), 923 kV (T3), 823.9 kV (T4)	779.4 kV	757.2 kV	438.2 kV	28.4 kV	43.9 kV	38.7 kV	2 kV	3.2 kV	2.8 kV	0.2 kV	0.4 kV	0.3 kV	0.12 kV	0.2 kV	0.15 kV
	3	None	1.07 MV (T1), 1.05 MV (T2), 1.12 MV (T3), 1.18 MV (T4)	1.04 MV	1.03 MV	612.1 kV	38.8 kV	60.4 kV	53.4 kV	1.7 kV	2.6 kV	2.3 kV	0.2 kV	0.25 kV	0.2 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (All Phases)	830.3 kV (T1), 1.01 MV (T2), 792.3 kV (T3), 765.9 kV (T4)	763.9 kV	760.4 kV	522.2 kV	29.4 kV	45.7 kV	40.8 kV	1.7 kV	2.6 kV	2.3 kV	0.2 kV	0.25 kV	0.2 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (Phase B)	973.8 kV (T1), 1.04 MV (T2), 917.3 kV (T3), 918.3 kV (T4)	946.2 kV	773.6 kV	529.9 kV	32.6 kV	49.1 kV	44.2 kV	1.7 kV	2.6 kV	2.3 kV	0.2 kV	0.25 kV	0.2 kV	0.1 kV	0.1 kV	0.1 kV
	4	None	1.06 MV (T1), 1.02 MV (T2), 1.13 MV (T3), 1.2 MV (T4)	1.03 MV	982.1 kV	622.9 kV	38 kV	58.8 kV	52.3 kV	2 kV	3.1 kV	2.8 kV	0.15 kV	0.25 kV	0.2 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (All Phases)	917.8 kV (T1), 771.9 kV (T2), 823.6 kV (T3), 784.6 kV (T4)	788.2 kV	758.1 kV	538.6 kV	29.6 kV	45.9 kV	41.1 kV	3 kV	3.1 kV	2.8 kV	0.15 kV	0.25 kV	0.2 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (Phase B)	1.02 MV (T1), 864.6 kV (T2), 948.7 kV (T3), 995.7 kV (T4)	971.6 kV	782 kV	551.2 kV	33.2 kV	49.7 kV	45 kV	4 kV	3.1 kV	2.8 kV	0.15 kV	0.25 kV	0.2 kV	0.1 kV	0.1 kV	0.1 kV

Figure 4.24: Results for 20 kA 1.2/50 μs direct stroke to the Phase B conductor with a surge capacitance.

- When one surge arrester in Phase B of 400 kV level is operating (Case 6), the results are slightly higher than Case 2 for Phase A of 400 kV level and all phases of 20 kV level; whereas, Phase B and Phase C of 400 kV level are almost same. Induced voltage on each level is below BIL.
- As a result, one surge arrester operation in Phase B of 400 kV level (Case 6) is sufficient to make the system safe as each voltage level is below BIL.

4.4.7 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase C Conductor Without a Surge Capacitance

In this part, the lightning source has been adjusted as 20 kA 1.2/50 μs and Phase C conductor of the tower was exposed to the lightning stroke. No surge capacitance is used in the network. The simulation results will be given in Figure 4.25 on the next page.

For the results of different cases and scenarios in 4.25, following discussions and comments can be made:

- When the lightning strikes to the Phase C conductor of the towers without the operation of any surge arresters (Case 1), all phases of 400 kV level are above BIL for 1 existing tower scenario, and below BIL for the other scenarios. All phases of 20 kV level are below BIL for all scenarios. Moreover, all phases of 6.9 kV level are below BIL for all scenarios.
- As the number of towers increases, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage on each level is below BIL.
- When one surge arrester in Phase C of 400 kV level is operating (Case 7), the results are slightly higher than Case 2 for Phase A and Phase B of 400 kV level and all phases of 20 kV level; whereas, Phase C of 400 kV level is almost same. Induced voltage on each level is below BIL.
- As a result, one surge arrester operation in Phase C of 400 kV level (Case 7) is sufficient to make the system safe as each voltage level is below BIL.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 20 kV Side			Induced Voltage Peak on 6.9 kV Side			Induced Voltage Peak on 690 V Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	1.42 MV (T1)	1.42 MV	1.44 MV	1.55 MV	108.6 kV	139.1 kV	132.8 kV	4.3 kV	5.9 kV	5.7 kV	0.8 kV	1.1 kV	1 kV	0.5 kV	0.7 kV	0.7 kV
		400 kV (All Phases)	641.1 kV (T2)	642.5 kV	675 kV	850.9 kV	52.8 kV	67.8 kV	65.4 kV	4.3 kV	5.9 kV	5.7 kV	0.8 kV	1.1 kV	1 kV	0.5 kV	0.7 kV	0.7 kV
		400 kV (Phase C)	751 kV (T1)	743.4 kV	750.1 kV	850.9 kV	56.8 kV	72.7 kV	69.5 kV	3.8 kV	5.3 kV	5.2 kV	0.8 kV	1.1 kV	1 kV	0.5 kV	0.7 kV	0.7 kV
2	1	None	929.1 kV (T1), 943.7 kV (T2)	927.4 kV	933.6 kV	991.3 kV	70.2 kV	89.9 kV	85.8 kV	4 kV	5.6 kV	5.5 kV	0.8 kV	1.1 kV	1 kV	0.3 kV	0.5 kV	0.4 kV
		400 kV (All Phases)	665.4 kV (T1), 666.2 kV (T2)	665.3 kV	679.6 kV	803.2 kV	52.4 kV	67.1 kV	64.3 kV	3.7 kV	5.1 kV	4.9 kV	0.8 kV	1.1 kV	1 kV	0.3 kV	0.5 kV	0.4 kV
		400 kV (Phase C)	739.7 kV (T1), 749.1 kV (T2)	739.9 kV	737.2 kV	803.2 kV	55.5 kV	71.1 kV	67.8 kV	3.7 kV	5.1 kV	4.9 kV	0.8 kV	1.1 kV	1 kV	0.3 kV	0.5 kV	0.4 kV
	2	None	965.2 kV (T1), 1.01 MV (T2)	952.2 kV	942.9 kV	988.6 kV	71.9 kV	91.8 kV	87.7 kV	3.4 kV	4.4 kV	4.2 kV	0.3 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	697.6 kV (T1), 774.9 kV (T2)	676.3 kV	689 kV	780.8 kV	52.8 kV	67.8 kV	65 kV	3.4 kV	4.4 kV	4.2 kV	0.3 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
		400 kV (Phase C)	761.9 kV (T1), 817.9 kV (T2)	741.9 kV	735.3 kV	782.1 kV	55.9 kV	71.4 kV	68.2 kV	3.4 kV	4.4 kV	4.2 kV	0.3 kV	0.4 kV	0.4 kV	0.2 kV	0.2 kV	0.2 kV
3	1	None	689.8 kV (T1), 697.8 kV (T2), 721.5 kV (T3)	693.5 kV	676.6 kV	988 kV	51.9 kV	66.1 kV	63.2 kV	4 kV	5.6 kV	5.4 kV	0.8 kV	1.1 kV	1 kV	0.5 kV	0.7 kV	0.7 kV
		400 kV (All Phases)	640.6 kV (T1), 644.7 kV (T2), 650.9 kV (T3)	640 kV	628.2 kV	801.4 kV	47.5 kV	60.7 kV	58.2 kV	3.7 kV	5.1 kV	5 kV	0.8 kV	1.1 kV	1 kV	0.5 kV	0.7 kV	0.7 kV
		400 kV (Phase C)	654 kV (T1), 653.1 kV (T2), 657.8 kV (T3)	659.4 kV	642.3 kV	801.4 kV	48.5 kV	61.8 kV	58.8 kV	3.7 kV	5.1 kV	5 kV	0.8 kV	1.1 kV	1 kV	0.5 kV	0.7 kV	0.7 kV
	2	None	713.4 kV (T1), 760.4 kV (T2), 725.8 kV (T3)	716 kV	704.5 kV	758.8 kV	53.5 kV	68.3 kV	65.2 kV	2.5 kV	3.3 kV	3.3 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	657 kV (T1), 702.8 kV (T2), 699.6 kV (T3)	652.9 kV	650.9 kV	698.8 kV	49.7 kV	63.6 kV	60.7 kV	2.5 kV	3.3 kV	3.3 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
		400 kV (Phase C)	679.7 kV (T1), 731.7 kV (T2), 703.4 kV (T3)	682.9 kV	674.9 kV	698.6 kV	51.3 kV	65.5 kV	62.5 kV	2.5 kV	3.3 kV	3.3 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
	3	None	724.7 kV (T1), 707.4 kV (T2), 829.4 kV (T3)	722.9 kV	726.1 kV	722.6 kV	54.8 kV	70 kV	66.8 kV	2.8 kV	3.6 kV	3.4 kV	0.2 kV	0.3 kV	0.3 kV	0.12 kV	0.18 kV	0.18 kV
		400 kV (All Phases)	678 kV (T1), 671.5 kV (T2), 793.5 kV (T3)	663.5 kV	687.1 kV	677.5 kV	50.7 kV	64.9 kV	62 kV	2.8 kV	3.6 kV	3.4 kV	0.2 kV	0.3 kV	0.3 kV	0.12 kV	0.18 kV	0.18 kV
		400 kV (Phase C)	703.8 kV (T1), 690.4 kV (T2), 818.1 kV (T3)	702.9 kV	706.9 kV	685 kV	52.8 kV	67.5 kV	64.3 kV	2.8 kV	3.6 kV	3.4 kV	0.2 kV	0.3 kV	0.3 kV	0.12 kV	0.18 kV	0.18 kV
4	1	None	585.2 kV (T1), 556.4 kV (T2), 571.1 kV (T3), 600.4 kV (T4)	578.4 kV	530.2 kV	987.9 kV	42.2 kV	55.9 kV	55.4 kV	4 kV	5.6 kV	5.4 kV	0.8 kV	1.1 kV	1 kV	0.5 kV	0.7 kV	0.7 kV
		400 kV (All Phases)	538 kV (T1), 530.5 kV (T2), 532.6 kV (T3), 530.8 kV (T4)	536.3 kV	502.3 kV	801.3 kV	39.9 kV	50.7 kV	48.8 kV	3.7 kV	5.1 kV	4.9 kV	0.8 kV	1.1 kV	2 kV	0.5 kV	0.7 kV	0.7 kV
		400 kV (Phase C)	538.2 kV (T1), 530.4 kV (T2), 532.79 kV (T3), 531.1 kV (T4)	536.6 kV	502.5 kV	801.3 kV	39.9 kV	50.7 kV	48.8 kV	3.7 kV	5.1 kV	4.9 kV	0.8 kV	1.1 kV	3 kV	0.5 kV	0.7 kV	0.7 kV
	2	None	566.9 kV (T1), 629.1 kV (T2), 625.8 kV (T3), 608.7 kV (T4)	554.5 kV	546.8 kV	655.7 kV	42.7 kV	54.9 kV	52.8 kV	2.5 kV	3.3 kV	3.2 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
		400 kV (All Phases)	564.2 kV (T1), 625.4 kV (T2), 621.5 kV (T3), 605.1 kV (T4)	552.2 kV	541.2 kV	646 kV	42.2 kV	54.3 kV	52.2 kV	2.5 kV	3.3 kV	3.2 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
		400 kV (Phase C)	564.5 kV (T1), 625.6 kV (T2), 621.6 kV (T3), 605.4 kV (T4)	552.6 kV	541.4 kV	646 kV	42.2 kV	54.3 kV	52.2 kV	2.5 kV	3.3 kV	3.2 kV	0.3 kV	0.4 kV	0.4 kV	0.15 kV	0.2 kV	0.2 kV
	3	None	565.1 kV (T1), 578.3 kV (T2), 633.7 kV (T3), 693.6 kV (T4)	583.9 kV	629.9 kV	595.1 kV	45.6 kV	58.8 kV	55.8 kV	2 kV	2.6 kV	2.4 kV	0.2 kV	0.25 kV	0.25 kV	0.1 kV	0.12 kV	0.12 kV
		400 kV (All Phases)	564.7 kV (T1), 575.4 kV (T2), 630.7 kV (T3), 689.8 kV (T4)	582 kV	625.8 kV	593.1 kV	45.4 kV	58.5 kV	55.5 kV	2 kV	2.6 kV	2.4 kV	0.2 kV	0.25 kV	0.25 kV	0.1 kV	0.12 kV	0.12 kV
		400 kV (Phase C)	565.1 kV (T1), 578.1 kV (T2), 633.4 kV (T3), 693.1 kV (T4)	583.8 kV	629.7 kV	594 kV	45.6 kV	58.7 kV	55.7 kV	2 kV	2.6 kV	2.4 kV	0.2 kV	0.25 kV	0.25 kV	0.1 kV	0.12 kV	0.12 kV
	4	None	555.9 kV (T1), 587 kV (T2), 655.1 kV (T2), 675.1 kV (T4)	584.8 kV	634.8 kV	546.4 kV	44.1 kV	56.9 kV	53.6 kV	2.3 kV	3 kV	2.8 kV	0.2 kV	0.2 kV	0.2 kV	0.1 kV	0.12 kV	0.12 kV
		400 kV (All Phases)	554.1 kV (T1), 584.8 kV (T2), 651 kV (T3), 672.1 kV (T4)	583.6 kV	629.7 kV	543.9 kV	43.8 kV	56.6 kV	53.4 kV	2.3 kV	3 kV	2.8 kV	0.2 kV	0.2 kV	0.2 kV	0.1 kV	0.12 kV	0.12 kV
		400 kV (Phase C)	555.8 kV (T1), 587 kV (T2), 655 kV (T3), 661.1 kV (T4)	584.8 kV	634.8 kV	546.4 kV	44.1 kV	56.9 kV	53.6 kV	2.3 kV	3 kV	2.8 kV	0.2 kV	0.2 kV	0.2 kV	0.1 kV	0.12 kV	0.12 kV

Figure 4.25: Results for 20 kA 1.2/50 μs direct stroke to the Phase C conductor without a surge capacitance.

4.4.8 Results for 20 kA 1.2/50 μs Direct Stroke to the Phase C Conductor With a Surge Capacitance

In this part, the lightning source has been adjusted as 20 kA 1.2/50 μs and the Phase C conductor of the tower was exposed to lightning stroke. A surge capacitance of 0.36 μF is used in the network. The results are demonstrated in Figure 4.26 on the next page.

For the results of different cases and scenarios in Figure 4.26, following discussions and comments can be made:

- For all scenarios, the values in 400 kV level are almost the same as the case without a surge capacitance; whereas, the values in 20 kV and 6.9 kV level are significantly less than the case without a surge capacitance.
- When the lightning strikes to the Phase C conductor of the towers without the operation of any surge arresters (Case 1), all phases of 400 kV level are above BIL for 1 existing tower scenario, and below BIL for the other scenarios. All phases of 20 kV level are below BIL for all scenarios. Moreover, all phases of 6.9 kV level are below BIL for all scenarios.
- As the number of towers increases, the magnitude of the induced voltages on each level decreases.
- As the stroke hits to the towers in the left side, the magnitude of the induced voltages on each level increases; however, the magnitude is still less than the scenario with the fewer towers.
- When one surge arrester in each phase of 400 kV level is operating (Case 2), induced voltage on each level is below BIL.
- When one surge arrester in Phase C of 400 kV level is operating (Case 7), the results are slightly higher than Case 2 for Phase A and Phase B of 400 kV level and all phases of 20 kV level; whereas, Phase C of 400 kV level is almost same. Induced voltage on each level is below BIL.
- As a result, one surge arrester operation in Phase C of 400 kV level (Case 7) is sufficient to make the system safe as each voltage level is below BIL.

Number of Towers	Tower Number Exposed to Stroke	Operating Surge Arresters	Induced Voltage Peak on Tower	Induced Voltage Peak on 400 kV Side			Induced Voltage Peak on 20 kV Side			Induced Voltage Peak on 6.9 kV Side			Induced Voltage Peak on 690 V Side			Induced Voltage Peak on 400 V Side		
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	1	None	1.41 MV (T1)	1.41 MV	1.43 MV	1.54 MV	62 kV	96.8 kV	89.7 kV	2.4 kV	4 kV	4.2 kV	0.5 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
		400 kV (All Phases)	641.1 kV (T2)	642.4 kV	674.8 kV	851.1 kV	30.2 kV	47.4 kV	44.4 kV	2.2 kV	3.7 kV	3.8 kV	0.5 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
		400 kV (Phase C)	751 kV (T1)	744.5 kV	749.5 kV	851.1 kV	32.5 kV	50.7 kV	46.9 kV	2.2 kV	3.7 kV	3.8 kV	0.5 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
2	1	None	929.1 kV (T1), 943.7 kV (T2)	925.7 kV	931.3 kV	988.5 kV	40.1 kV	62.6 kV	57.8 kV	2.3 kV	3.8 kV	4 kV	0.4 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
		400 kV (All Phases)	665.4 kV (T1), 666.2 kV (T2)	665.1 kV	679.5 kV	803.5 kV	30 kV	46.8 kV	43.6 kV	2.1 kV	3.5 kV	3.6 kV	0.4 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
		400 kV (Phase C)	739.7 kV (T1), 749.1 kV (T2)	739.6 kV	736.8 kV	803.5 kV	31.8 kV	49.5 kV	45.8 kV	2.1 kV	3.5 kV	3.6 kV	0.4 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
	2	None	965.2 kV (T1), 1.01 MV (T2)	949.6 kV	940.6 kV	985.8 kV	41.1 kV	63.8 kV	59.1 kV	1.9 kV	3.1 kV	2.9 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.15 kV	0.15 kV
		400 kV (All Phases)	697.6 kV (T1), 774.9 kV (T2)	676.2 kV	688 kV	781 kV	30.2 kV	47.3 kV	44.1 kV	1.9 kV	3.1 kV	2.9 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.15 kV	0.15 kV
		400 kV (Phase C)	761.9 kV (T1), 817.9 kV (T2)	741.5 kV	733.6 kV	782.2 kV	32 kV	49.7 kV	46 kV	1.9 kV	3.1 kV	2.9 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.15 kV	0.15 kV
3	1	None	689.8 kV (T1), 697.8 kV (T2), 721.5 kV (T3)	691.5 kV	675.5 kV	984.6 kV	29.6 kV	45.9 kV	42.6 kV	2.3 kV	3.8 kV	3.9 kV	0.4 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
		400 kV (All Phases)	640.6 kV (T1), 644.7 kV (T2), 650.9 kV (T3)	639.8 kV	626.7 kV	801.6 kV	27.2 kV	42.3 kV	39.4 kV	2.1 kV	3.5 kV	3.6 kV	0.4 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
		400 kV (Phase C)	654 kV (T1), 653.1 kV (T2), 657.8 kV (T3)	658.7 kV	641.8 kV	801.6 kV	27.7 kV	43 kV	39.7 kV	2.1 kV	3.5 kV	3.6 kV	0.4 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
	2	None	713.4 kV (T1), 760.4 kV (T2), 725.8 kV (T3)	714.9 kV	700.5 kV	757.1 kV	30.6 kV	47.6 kV	44 kV	1.4 kV	2.3 kV	2.2 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (All Phases)	657 kV (T1), 702.8 kV (T2), 699.6 kV (T3)	653.1 kV	650.9 kV	698 kV	28.4 kV	44.2 kV	40.8 kV	1.4 kV	2.3 kV	2.2 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (Phase C)	679.7 kV (T1), 731.7 kV (T2), 703.4 kV (T3)	682.5 kV	674.5 kV	698.2 kV	29.3 kV	45.6 kV	42.2 kV	1.4 kV	2.3 kV	2.2 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.1 kV	0.1 kV
	3	None	724.7 kV (T1), 707.4 kV (T2), 829.4 kV (T3)	720.6 kV	724.7 kV	721.4 kV	31.3 kV	48.7 kV	45 kV	1.6 kV	2.5 kV	2.3 kV	0.15 kV	0.2 kV	0.2 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (All Phases)	678 kV (T1), 671.5 kV (T2), 793.5 kV (T3)	663.4 kV	685.2 kV	676.8 kV	29 kV	45.3 kV	41.9 kV	1.6 kV	2.5 kV	2.3 kV	0.15 kV	0.2 kV	0.2 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (Phase C)	703.8 kV (T1), 690.4 kV (T2), 818.1 kV (T3)	701.1 kV	703.4 kV	684.6 kV	30.2 kV	47 kV	43.3 kV	1.6 kV	2.5 kV	2.3 kV	0.15 kV	0.2 kV	0.2 kV	0.1 kV	0.1 kV	0.1 kV
4	1	None	585.2 kV (T1), 556.4 kV (T2), 571.1 kV (T3), 600.4 kV (T4)	577.1 kV	532.4 kV	984.5 kV	24 kV	39.4 kV	38.6 kV	2.3 kV	3.8 kV	3.9 kV	0.4 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
		400 kV (All Phases)	538 kV (T1), 530.5 kV (T2), 532.6 kV (T3), 530.8 kV (T4)	536.1 kV	502.1 kV	801.6 kV	22.8 kV	35.2 kV	33 kV	2.1 kV	3.5 kV	3.6 kV	0.4 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
		400 kV (Phase C)	538.2 kV (T1), 530.4 kV (T2), 532.79 kV (T3), 531.1 kV (T4)	536.6 kV	502.5 kV	801.6 kV	22.8 kV	35.2 kV	33 kV	2.1 kV	3.5 kV	3.6 kV	0.4 kV	0.7 kV	0.8 kV	0.3 kV	0.5 kV	0.5 kV
	2	None	566.9 kV (T1), 629.1 kV (T2), 625.8 kV (T3), 608.7 kV (T4)	553.3 kV	546.2 kV	654.5 kV	24.4 kV	38.3 kV	35.9 kV	1.4 kV	2.3 kV	2.2 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.12 kV	0.12 kV
		400 kV (All Phases)	564.2 kV (T1), 625.4 kV (T2), 621.5 kV (T3), 605.1 kV (T4)	551.1 kV	540.7 kV	645.2 kV	24.2 kV	37.9 kV	35.5 kV	1.4 kV	2.3 kV	2.2 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.12 kV	0.12 kV
		400 kV (Phase C)	564.5 kV (T1), 625.6 kV (T2), 621.6 kV (T3), 605.4 kV (T4)	551.7 kV	541 kV	645.2 kV	24.2 kV	37.9 kV	35.5 kV	1.4 kV	2.3 kV	2.2 kV	0.2 kV	0.3 kV	0.3 kV	0.1 kV	0.12 kV	0.12 kV
	3	None	565.1 kV (T1), 578.3 kV (T2), 633.7 kV (T3), 693.6 kV (T4)	581.8 kV	628.2 kV	594.1 kV	26 kV	41 kV	37.7 kV	1.1 kV	1.8 kV	1.6 kV	0.1 kV	0.18 kV	0.15 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (All Phases)	564.7 kV (T1), 575.4 kV (T2), 630.7 kV (T3), 689.8 kV (T4)	580.1 kV	624.3 kV	592.2 kV	25.9 kV	40.8 kV	37.5 kV	1.1 kV	1.8 kV	1.6 kV	0.1 kV	0.18 kV	0.15 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (Phase C)	565.1 kV (T1), 578.1 kV (T2), 633.4 kV (T3), 693.1 kV (T4)	581.7 kV	628 kV	593 kV	25.9 kV	40.8 kV	37.5 kV	1.1 kV	1.8 kV	1.6 kV	0.1 kV	0.18 kV	0.15 kV	0.1 kV	0.1 kV	0.1 kV
	4	None	555.9 kV (T1), 587 kV (T2), 655.1 kV (T2), 675.1 kV (T4)	581.6 kV	632.8 kV	546.8 kV	25.1 kV	39.7 kV	36.1 kV	1.3 kV	2 kV	1.8 kV	0.1 kV	0.16 kV	0.14 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (All Phases)	554.1 kV (T1), 584.8 kV (T2), 651 kV (T3), 672.1 kV (T4)	580.6 kV	628.2 kV	542.4 kV	25 kV	39.6 kV	36 kV	1.3 kV	3 kV	1.8 kV	0.1 kV	0.16 kV	0.14 kV	0.1 kV	0.1 kV	0.1 kV
		400 kV (Phase C)	555.8 kV (T1), 587 kV (T2), 655 kV (T3), 661.1 kV (T4)	581.5 kV	632.8 kV	546.8 kV	25 kV	39.6 kV	36 kV	1.3 kV	4 kV	1.8 kV	0.1 kV	0.16 kV	0.14 kV	0.1 kV	0.1 kV	0.1 kV

Figure 4.26: Results for 20 kA 1.2/50 μs direct stroke to the Phase C conductor with a surge capacitance.

5 Conclusion

In this thesis work, 2 NPPs exposed to lightning stroke have been investigated. Firstly, the equipment of the NPPs has been modeled properly. Then, different magnitudes of lightning have been used according to the standards, and the lightning induced over-voltages in NPPs have been simulated for different cases and scenarios. Finally, viable protection solutions with different combinations of the surge arresters have been proposed.

As the modeling of the power transformers have been made using R, L, and C components, the turn ratio is dominated by capacitive division in high frequencies. Therefore, the small changes in the capacitance values affect the transferred voltage to the other side of the transformer. In the model, capacitance values of the transformers were tuned so that the turn ratio can be kept within a range. Also, in the simulation models, cables have not been used between the busbars. Voltage drop on the cables had been avoided so that the worst case for the voltage levels could have been investigated. Therefore, this study analyzes the results and proposes protection ways for the worst case scenario.

For the results of the first NPP without usage of a surge capacitance in 15.75 kV level, if the magnitude of the lightning is 200 kA and it strikes to the ground wire of the tower, one surge arrester in each phase of 400 kV and 15.75 kV levels should operate to be protected from the lightning in a best way. However, with this protection, although the other levels are below BIL, Phase A of 400 kV level is above BIL. In order to make it below BIL, a surge arrester with the different ratings might be used in 400 kV level. If the magnitude of the lightning is 20 kA and it strikes to the phase conductor of the tower, only one surge arrester operation in the corresponding phase of 400 kV level is enough to protect the system. When there is a surge capacitance of 0.36 μF is connected to 15.75 kV level, it reduces the induced voltages in 15.75 kV level significantly. For 200 kA stroke to the ground wire of the tower, if there is a surge capacitance in 15.75 kV level, the operation of the surge arresters in that level is unnecessary. With operation of only 400 kV level surge arresters, induced voltage magnitudes in 15.75 kV level becomes lower than BIL thanks to the surge capacitance. Also, there is no significant effect of using the surge arresters in 6 kV level, although the surge arresters in 15.75 kV level are decreasing the induced voltage value considerably.

For the results of the second NPP without usage of a surge capacitance in 20 kV level, if the magnitude of the lightning is 200 kA and it strikes to the ground wire of the tower, one surge arrester in each phase of 400 kV level should operate to be protected from the lightning in a best way. There is no need to operate the surge arresters in 20 kV level in contrast to the first NPP since the BIL of the same level is almost double for the second NPP for the same level. However, with this protection, although the other levels are below BIL, Phase A of 400 kV level is above BIL. In order to make it below BIL, a surge arrester with different ratings might be used in 400 kV level. If the magnitude of the lightning is 20 kA and it strikes to the phase conductor of the tower, only one surge arrester operation in the corresponding phase of 400 kV level is enough to protect the system. When there is a surge capacitance of 0.36 μF is connected to 20 kV level, it reduces the induced voltages in 20 kV level significantly. However, protection ways are the same as the case without a surge capacitance because operation of the surge arresters in 20 kV level is unnecessary for both studies with 200 kA and 20 kA lightning magnitudes. Also, there is no significant effect of using the surge arresters in 6.9 kV level, although the surge arresters in 20 kV level are decreasing the induced voltage value considerably.

The induced voltage on the HV sides of 415/15.75 kV and 415/21.5 kV transformers are not affected by the parameters of the transformers a lot. Instead, they are mostly affected by the parameters of towers and overhead lines. Thus, it can be stated that the induced voltage on 400 kV level is more reliable compared to other levels. On the other hand, the induced voltage on the LV sides of 415/15.75 kV and 415/21.5 kV transformers (15.75 kV level for the first NPP and 20 kV level for the second NPP) are affected by the parameters of the transformer more compared to HV side.

The effect of tower number and the location of the stroke have also been investigated in the simulations. As the tower number increases, the induced voltage on the system reduces. Therefore, there should be more tower to lessen the effect of lightning on the system. Also, it has been observed that as the lightning strikes to the left towers, the value of induced voltage increases due to traveling waves. Precautions should be taken by taking this result into account.

To conclude, the main objectives of the thesis work have been achieved. The modeling has been made properly, the simulations have been taken precisely, and the protection ways have been proposed in detail. For better results in the future studies, it is recommended to include magnetic characteristics of the transformers to see their effect in flux saturation and thereby over-voltage transfer. Also, the grounding systems of the towers and the other equipment are needed in detail because grounding the part is one of the key factors determining the induced over-voltage distribution. Lastly, surge arresters with different ratings might be chosen to mitigate the induced voltages more and make Phase A of 400 kV level under BIL when the lightning current magnitude is 200 kA.

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A FRA Data of 415/15.75 kV Transformer

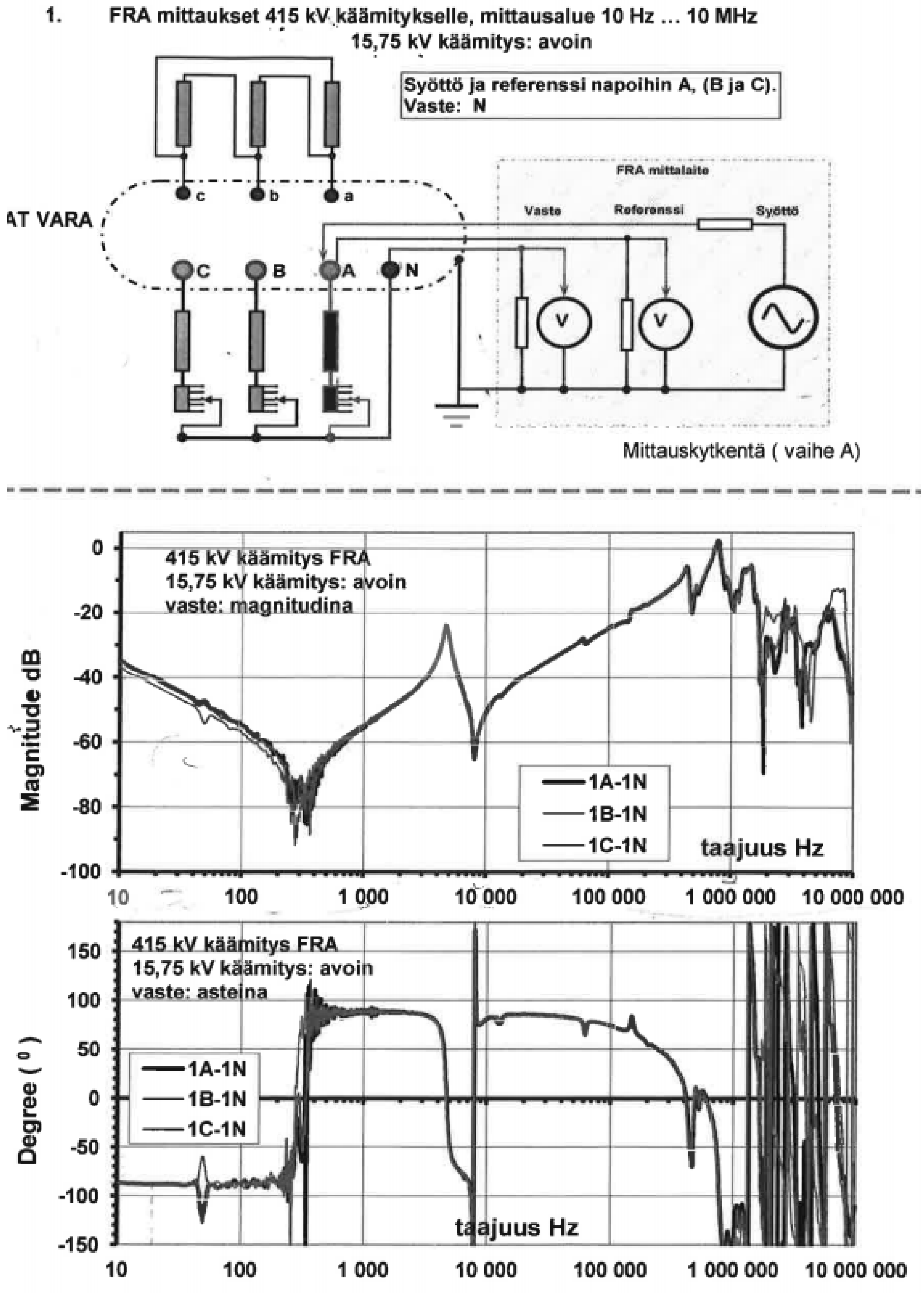

Figure A1: FRA of HV side of 415/15.75 kV transformer.

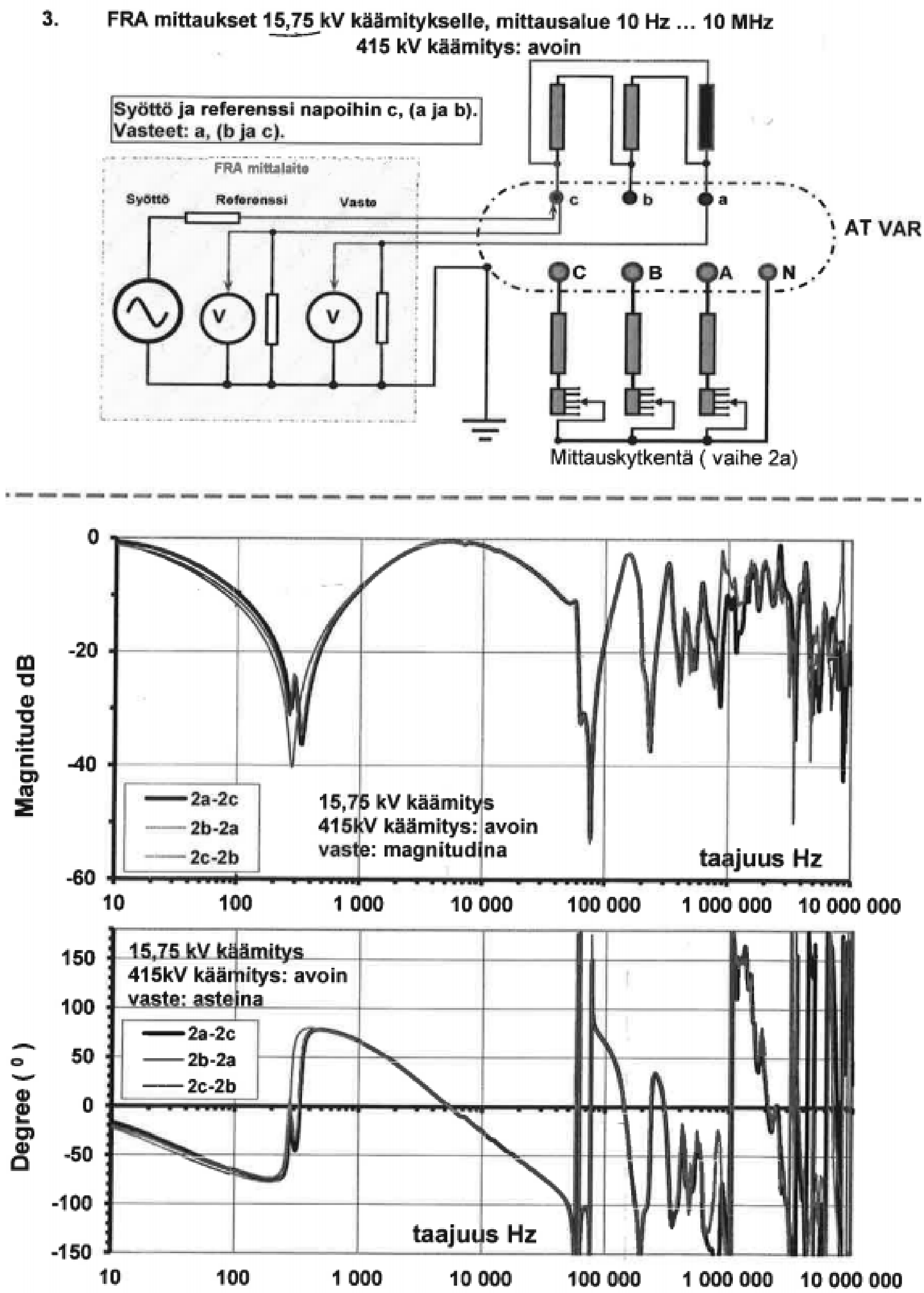

Figure A2: FRA of LV side of 415/15.75 kV transformer.

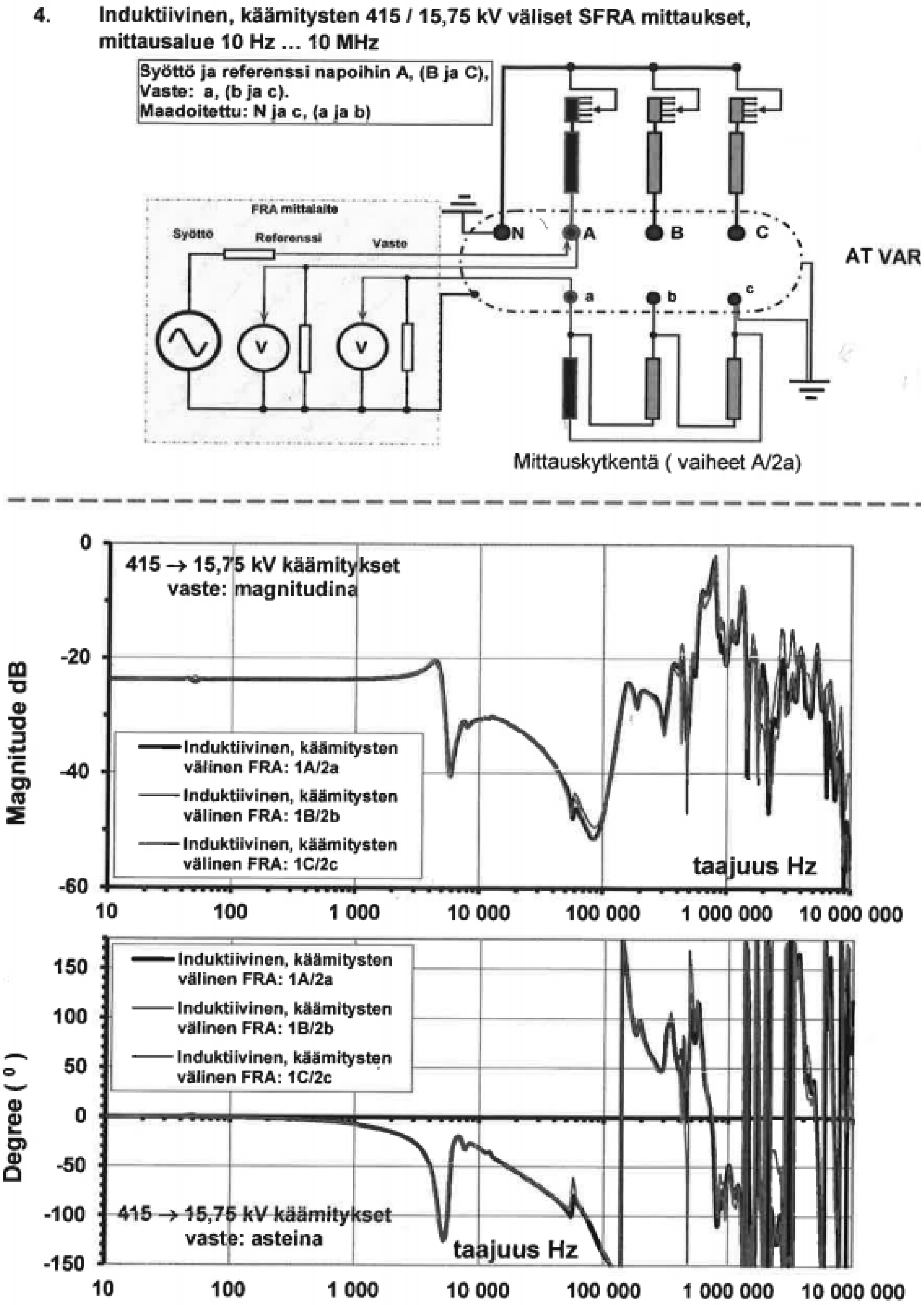

Figure A3: FRA between HV & LV sides of 415/15.75 kV transformer.

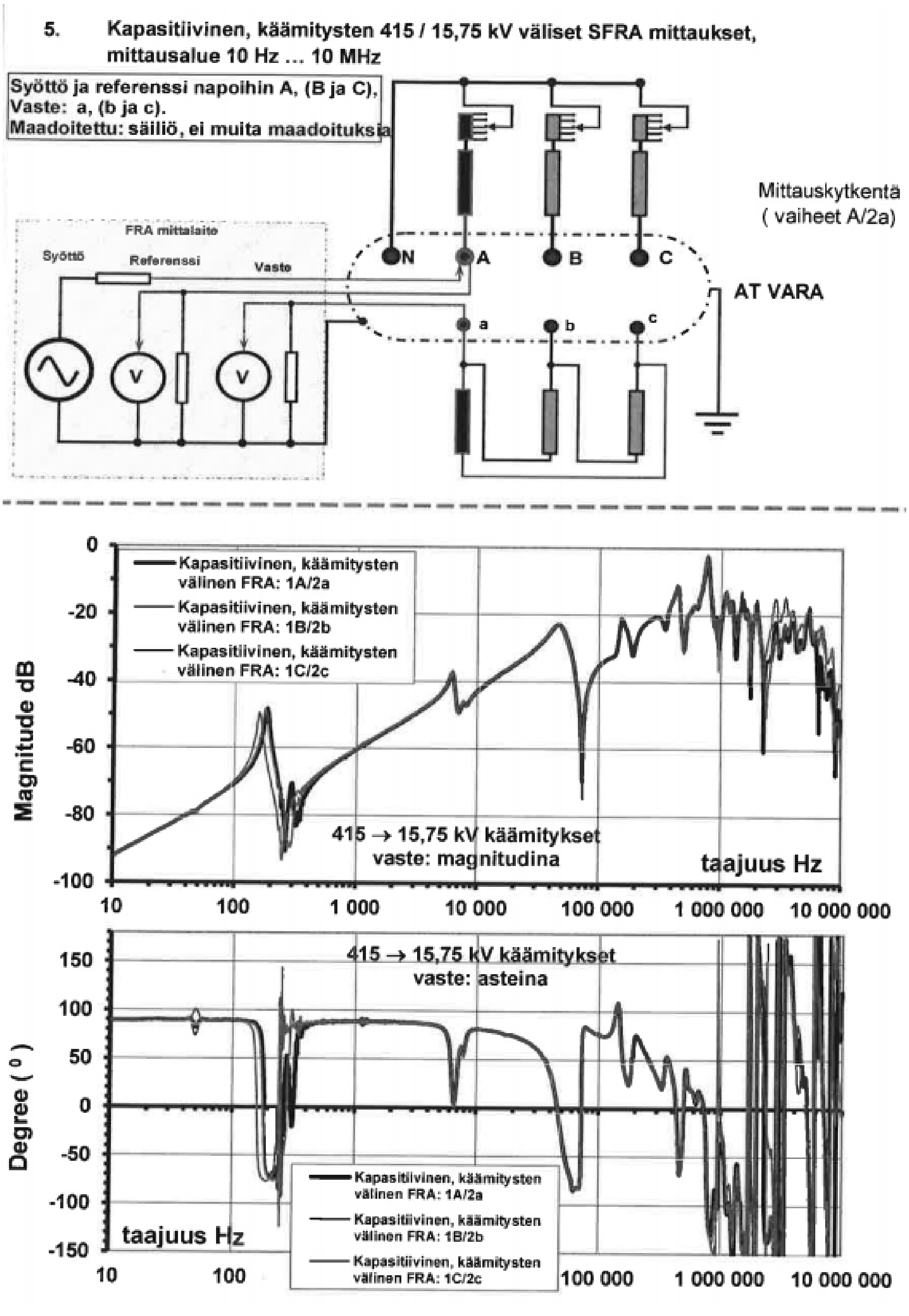

Figure A4: FRA between HV & LV sides of 415/15.75 kV transformer.

B FRA Data of 415/21.5 kV Transformer

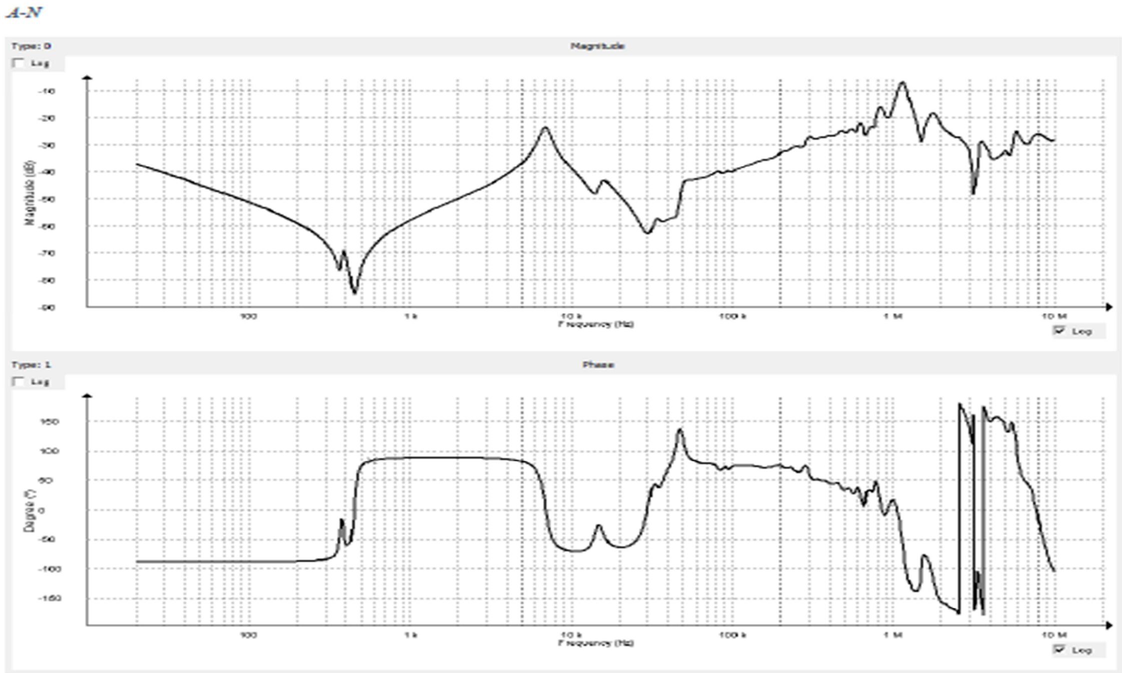

Figure B1: FRA between A-N of 415/21.5 kV transformer.

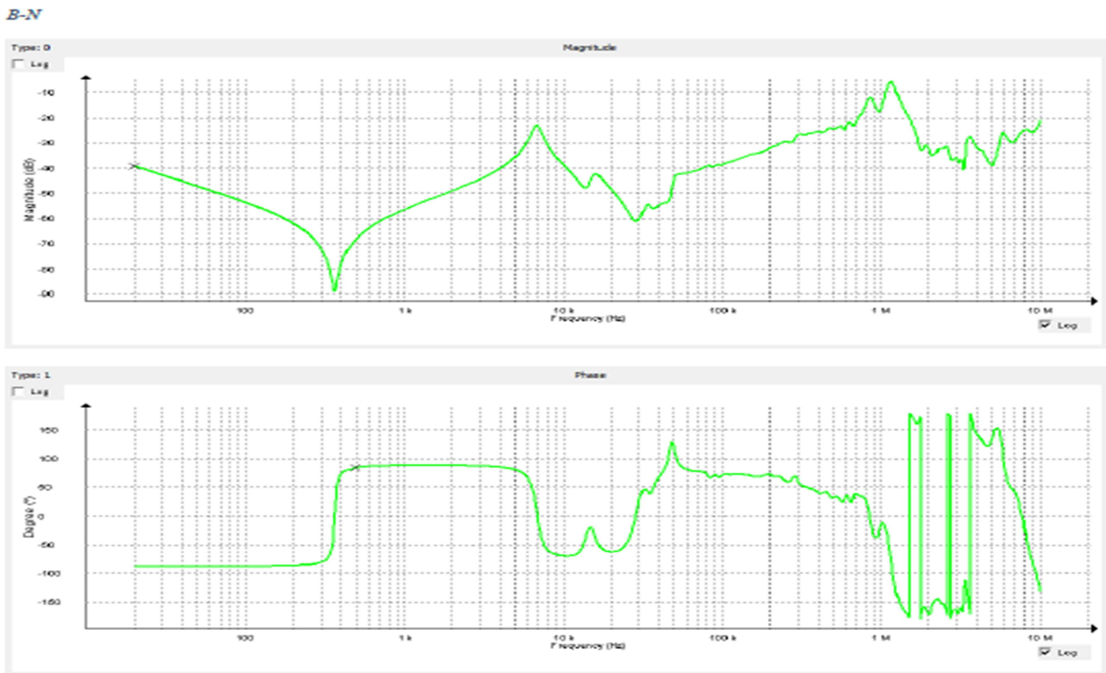

Figure B2: FRA between B-N of 415/21.5 kV transformer.

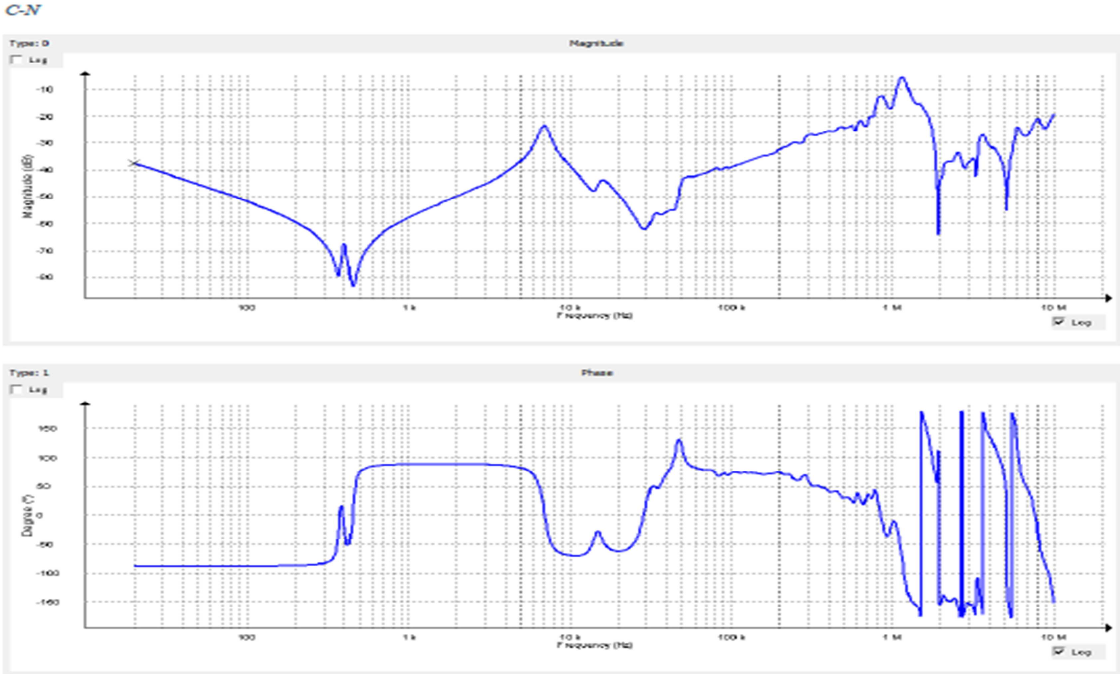

Figure B3: FRA between C-N of 415/21.5 kV transformer.

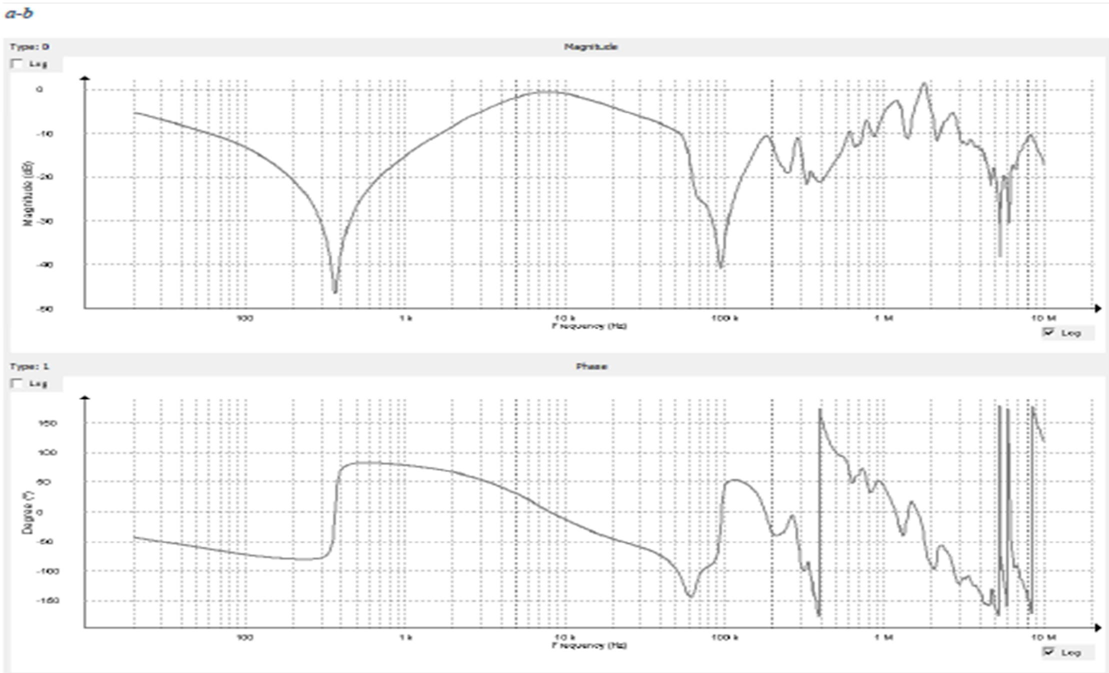

Figure B4: FRA between a-b of 415/21.5 kV transformer.

b-c

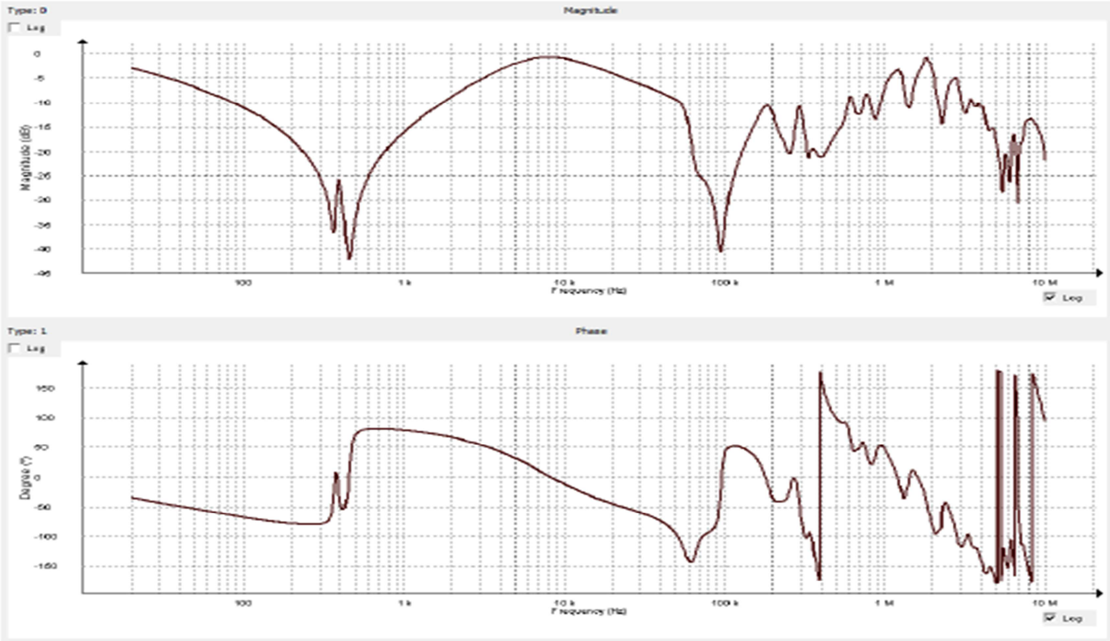

Figure B5: FRA between b-c of 415/21.5 kV transformer.

c-a

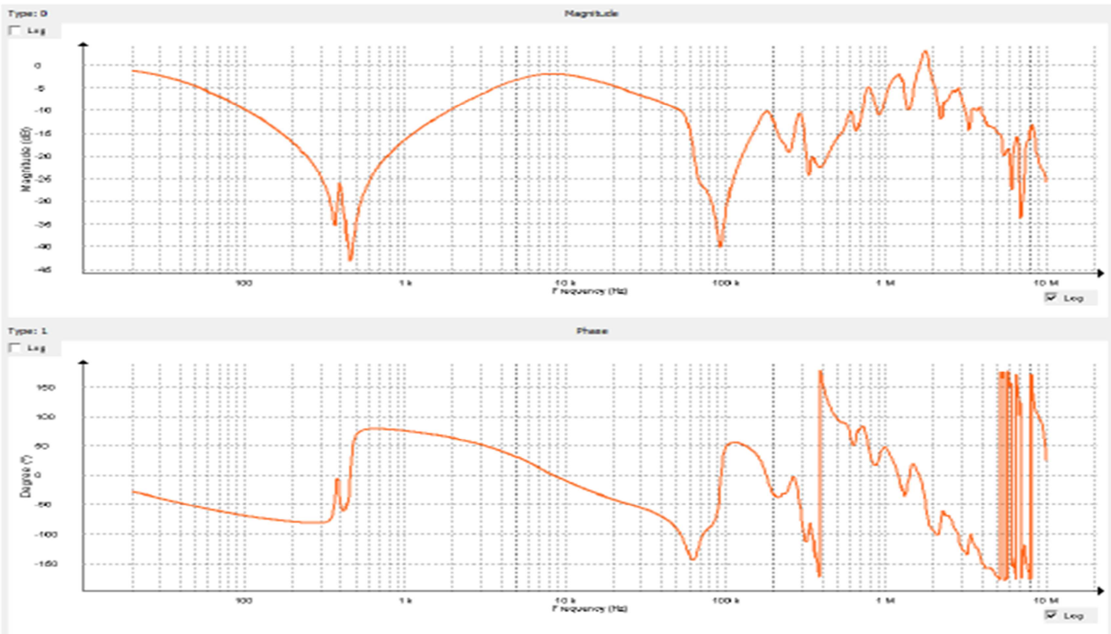

Figure B6: FRA between c-a of 415/21.5 kV transformer.

C Surge Arrester Characteristics

Table C1: V-I curve characteristics of A_0.

I (kA)	**V (pu)**
0.01	1.4
0.1	1.54
1	1.68
2	1.74
4	1.8
6	1.82
8	1.87
10	1.9
12	1.93
14	1.97
16	2
18	2.05
20	2.1

Table C2: V-I curve characteristics of A_1.

I (kA)	**V (pu)**
0.1	1.23
1	1.36
2	1.43
4	1.48
6	1.5
8	1.53
10	1.55
12	1.56
14	1.58
16	1.59
18	1.6
20	1.61